CIP foundation

How to establish a market for CCS with biochar in Denmark

February 2024

Preface

In this report, the CIP Foundation presents an action plan for market-driven production of biochar in Denmark that can help agriculture achieve its carbon reduction targets, and Denmark in achieving its national climate targets.

The point of departure is to exploit the technological opportunities for good climate solutions with huge potentials and possible co-benefits.

The plan has been prepared to promote the biochar market and increase interest from investors and other value chain participants, thus establishing a foundation for market-driven negative emissions based on feedstock.

Food production is today one of the largest sources of global anthropogenic climate change. In Denmark, agriculture accounts for almost one-quarter of Danish emissions, primarily through natural biological processes*. Danish agriculture and food production is trapped between requirements for reducing their climate footprint and investing more in the green transition, and consistent needs for increasing food production and exports.

With respect to the climate, the world needs to produce more climate-efficient food products on smaller areas. Development and use of new solutions can make Danish agriculture and food production a climate role model, showing how lower emissions can be compatible with continued growth and exports.

* [Hvad er CO2? (lf.dk)]

The Danish 2021 agreement on a green transition of the agricultural sector requires that the majority of carbon reductions in agriculture must be realised through new technologies, and not through decreasing total agricultural production. With the agreement, the Danish Parliament decided that pyrolysis and biochar production are to be key instruments in reducing emissions of green house gases from agriculture, with a potential of up to 2 million tonnes of carbon storage per year by 2030.

Pyrolysis is a flexible technology that can be adapted to changes in agriculture and can generate added value for a large number of crop residues and other agricultural residues. If carbon storage is sold as a service, i.e. through climate certificates, the technology can potentially be rolled out on market terms, thereby releasing resources for further investment in the green transition. With clear framework conditions, biochar could play a crucial role in this transition. Biochar has the potential to become the same benefit for agriculture as wind power has been for the energy sector.

Biochar is a climate measure and a stable type of carbon storage, similar to DACCS and BECCS. This is not about competing measures, but rather measures which supplement each other. Agriculture can benefit from a measure that offers long-term storage of the CO_2 absorbed by plants. Industry and the energy sector need measures which can capture carbon from production and store it.

Sometimes, carbon storage is criticised with the suggestion that it would be better to invest in real carbon reductions rather than storage technologies. It is true that substantial reductions must be made in the coming years, but one strategy does not rule out the other. If we are to meet the targets in the Paris Agreement, according to the UN Intergovernmental Panel on Climate Change (IPCC) we need to use negative emissions technologies. We must not only reduce carbon emissions; we must also take existing greenhouse gases out of the atmosphere.

The CIP Foundation's action plan for market-driven production of biochar should be seen in context with our vision for sustainable agriculture based on innovation and the use of new technologies. There is also the aim that Denmark should continue to be a front-runner and maintain its strong position on global markets.

The report can be read as a whole, or it can be used as a reference for specific interests. Some of the points appear several times – this is because they are important!

In 2024, the CIP Foundation will follow up on this report, with focus on the export opportunities in carbon storage using biochar.

We hope that the report is read in the light of the intention for which it was written.

Enjoy the read!

Anne Arhnung
Board Member at the CIP Foundation

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Managing Partner of the CIP Foundation

Summary

Biochar has the potential to play a major role in the transition of Danish agriculture. It is a mature technology that can store carbon effectively for many centuries. The socio-economic abatement costs of carbon sequestration with biochar are competitive amongst other climate measures.

The technology behind biochar can be rolled out on market terms, thereby releasing resources for further investment in the green transition. Market-driven CO_2 reductions in agriculture require that biochar sequestration be paid for through carbon credits, for example. An initial subsidy scheme can relieve some of the current uncertainty in the business case today. The absence of direct regulation around biochar is a source of uncertainty and is an obstacle to market development.

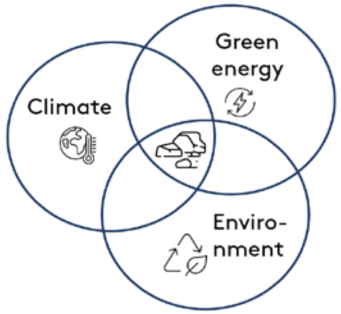
NEW CLIMATE MEASURE BASED ON WELL ESTABLISHED TECHNOLOGY

Biochar as a recognised and effective climate measure is relatively new both in Denmark and abroad. On the other hand, biochar production exploits nature's own CCS, and we have been making biochar for many years.

We all know that plants absorb CO_2 from the atmosphere through nature's own photosynthesis process. When you heat plant residues, for example grass, straw or wood, in a pyrolytic oven to around 500-600 °C in an oxygen-limited environment, the carbon from the biomass is distributed fairly evenly between gasses (green energy) and a stable residual product (biochar), which can store the carbon stably for a very long time.

Making biochar from biomass residues, in this way capturing and removing CO_2 from the atmosphere, and then storing it, is a negative emissions technology.

Figure A: *Biochar is beneficial on several parameters*



Source: The CIP Foundation's own graphic

TECHNOLOGY WITH THREE CLEAR BENEFITS

Pyrolysis of biomass residues can benefit in three important areas simultaneously:
The pyrolysis process generates green energy in the form of pyrolysis gas and bio-oils that can be used as green fuels, and the process also generates surplus heat that can be used for district heating or to heat installations or buildings. This type of green energy does not depend on the wind blowing or the sun shining, and is therefore a good supplement in future energy systems.
The climate benefits because biomass residues are used in a pyrolysis plant instead of, for example being spread on a field to decay. Processing prevents emissions of powerful greenhouse gasses from the biomass residues, and the green energy from this process can be used to displace other climate-impacting alternatives. Finally, it has been documented that biochar in itself can serve as a CCS technology. This is new.

"Biochar has a number of positive side-effects when it used on agricultural land. The soil becomes better at retaining water and this benefits crops, and it is possible to recirculate important nutrients such as phosphorus and potassium to nutrient-poor areas."
- The CIP Foundation

On the other hand, there is nothing new about the possible environmental benefits of using biochar in the soil. In fact, this is why biochar has been made for many years. In other countries, biochar has been used as a natural means of enriching the soil for many years. People in the Amazon region started using biochar to enrich the soil more than 2,500 years ago. The soil in the rain forest is often sandy and infertile below the first, thin soil layer. Adding biochar made it possible to transform the soil and make it richer and more fertile to cultivate food.

In Europe and a number of other countries, biochar is today used especially to improve the soil on farms and as a fertiliser for gardens and parks.

Biochar makes the soil more resistant to drought, it reduces emissions of potent climate gasses from the soil, and can also reduce nitrogen leaching from the soil to water bodies.

Biochar can also be used in other places, for example as a feed supplement, in building materials and insulation, in soil remediation and filtration, or even in health products.

EFFECTIVE CARBON STORAGE AND ADDITIONAL CLIMATE IMPACTS

Even though the biochar is used as fertiliser, for example, it still stores the carbon stably and for a long time.

80 % of the carbon in biochar will still be there after 100 years and...

75 % will be there after 1,000

"There is scientific consensus that biochar is a reliable mitigation measure against climate change with long-term sequestration effects."
- The CIP Foundation

After only a few years, biochar stores more carbon net compared with the alternative of spreading residue straw or biogas fibres on fields.

"Besides the direct carbon storage, which removes CO_2 from the atmosphere, there are further positive climate impacts in the form of emissions avoided and fuel displacement."
- The CIP Foundation

The climate impacts of Danish-produced biochar are encouraging. In general, one tonne of dry matter of biomass residues can be converted to a minimum of one tonne of climate benefits. Straw and residual fibres from biogas have the largest total climate impacts long-term, while processing sewage sludge into biochar, for example, has more short-term positive climate impacts in the form of emissions prevented.

1 tonne of biochar ~ 2 tonnes of stored carbon

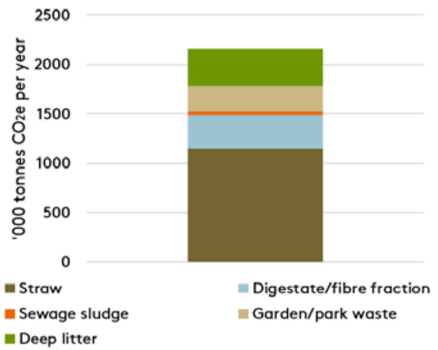
ENOUGH BIOMASS RESIDUALS TO MEET POLITICAL OBJECTIVES

Biochar is the last phase in a circular use of biomass, and it is based on residues with no appreciable alternative use. These residues include straw and other crop residues, residual biogas fibres, and sewage sludge, and can have added commercial value if it is used in the pyrolysis process and converted to green energy and biochar that can store CO_2.

"....and there are enough biomass residues to achieve the goal in the political agreement on a green transition of the agricultural sector to store 2 million tonnes of CO_2e annually."
- The CIP Foundation

Straw residues, residual fibres from biogas production and deep litter are particularly important in production of biochar because they contain relatively high amounts of carbon. The good news is that there are enough biomass residues to achieve the goal in the political agreement on a green transition of the agricultural sector to store 2 million tonnes of CO_2e annually. And there is great potential for more biomass residues from Danish agriculture, with up to 10 million tonnes of bioresources in 2030, see Det Nationale Bioøkonomipanel (2022). Primarily more residual straw and hay, which are very suitable for making biochar.

***Figure B:** Available biomass residues can support the storage of 2 million tonnes carbon*



Source: NIRAS (2023)

Biochar is also a good opportunity to reuse phosphorus from the biomass and redistribute it, thereby avoiding imports of phosphorus, which is otherwise a scarce resource. In practice, phosphorus caps for agricultural land put a limit on the amount of biochar that can be spread on fields.

PAYMENT FOR CARBON STORAGE CAN ENABLE PYROLYSIS TECHNOLOGY ON MARKET TERMS

Building pyrolysis plants requires major initial investments, and this means that the regulatory framework and future long-term revenue flows must be clear. There must be clear agreements between parties for biomass residues as input and biochar as output, and there must be payment for the costs of CO_2 storage.

"The costs of CCS using biochar can be covered through climate credits, CCS subsidies for a period, or through a higher willingness to pay from consumers for the products made within the value chain."
- The CIP Foundation

Analyses of the value chain and the potential revenue flows show that the technology behind biochar could be rolled out on market terms, thereby releasing further resources for investment in green transition.

".. pyrolysis and biochar are at a technological stage with potential for deployment on market terms and with contributions to CCS in the agricultural sector, where there are no other alternatives at this scale."
- The CIP Foundation

Commercialisation of carbon storage with biochar requires collaboration across sectors and stakeholders that do not necessarily work together normally, and it requires that everyone involved profits from participating in the value chain.

In simple terms, the value chain will consist of 1) a supplier of biomass (e.g. agriculture or biogas plants), 2) a pyrolysis plant, 3) receivers of biochar (e.g. agriculture) 4) receivers of energy products (e.g. shipping companies) and 5) receivers of surplus heat from the pyrolysis plant (e.g. a heating plant).

WHAT AFFECTS PROFITABILITY?

The business case depends on the biomass used, the need for pre-processing, the energy and carbon content in the biomass, and the sales prices of energy in the form of heat and green petroleum products. Some biomass residues are almost free, such as residual fibres from biogas, while other biomass costs money, such as straw residues. Moreover, there is payment for receiving some residues, such as sewage sludge. The different types of biomass also differ according to the required amount of dehydration and separation prior to the pyrolysis treatment.

Profitability is increased by symbioses and combining locations, i.e. if the pyrolysis plant is located close to an input supplier. This could be a biogas plant, a wastewater treatment plant, or close to an output receiver, for example an energy utility, or close to infrastructure such as the district heating grid.

"If the value chain is to be financially sustainable, agriculture has to benefit from supplying feedstock and subsequently using the biochar on fields."
- The CIP Foundation

If biochar production and use in agriculture is to be profitable, there must be revenues for carbon storage in biochar which, together with the revenues from energy, can reward both the farm supplying feedstock, the pyrolysis plant producing biochar, and the farm receiving biochar and storing it.

In other words, someone has to pay for the biochar's positive impact on the climate!

The CIP Foundation has examined the profitability of CCS with biochar for the whole value chain. The conclusion is that, today, producing biochar from residual fibres from biogas is profitable in a simple set-up where pyrolysis gas is also produced. It is also profitable with biochar made from residual straw, provided that bio-oil is also produced. However, the business cases are dependent on co-financing of around DKK 400-700 per tonne for carbon storage.

Biochar from sewage sludge will also be profitable if the willingness of to pay for the processing of the sludge from the waste water plants gets slightly higher than the current payment to farmers for directly applying the sludge to their fields

CLIMATE CREDITS CAN CO-FINANCE CARBON STORAGE IN BIOCHAR

A carbon removal certificate is proof that one tonne of CO_2 has been removed from the atmosphere. When a certificate is then traded, it is called a climate credit.

There are good prospects for co-financing carbon storage in biochar through the growing global market for climate credits. This is because the technology supplies stable and long-term storage which cannot be reversed, and as it constitutes a readily communicated solution with several co-benefits.
The market for climate credits is in rapid development, driven by increasing demand for products with a lower climate footprint, and by companies with ambitious climate targets (e.g. net-zero emissions), that cannot necessarily reduce all emissions among themselves and their closest cooperation partners. Climate credits can be used as set-off in companies' climate accounts.

"Willingness to pay for climate credits primarily depends on the duration of the climate impact, the documentation, and certainty of the project."
- The CIP Foundation

A climate credit based on CCS with biochar costs around EUR 130 per tonne CO_2e. In the summer of 2023, the first climate credits based on Danish biochar were sold by SkyClean for EUR 160 per tonne CO_2e.

NEED FOR A STANDARDISED FRAMEWORK

The market for climate credits, including biochar credits, can be strengthened by establishing a uniform, standardised certification framework with clear guidelines for how climate impacts are calculated, used and communicated, and with clear verification from an independent third party. A fixed system for Monitoring, Reporting and Verification (MRV) is also required.
There are currently several standards globally on the voluntary market for climate credits. Even though they also have MRV systems, it can be difficult to navigate between the various standards. The EU is working on a standardised certification framework for carbon removal, and this is expected to be in place around 2028. This framework could become the norm for future carbon removal certification.

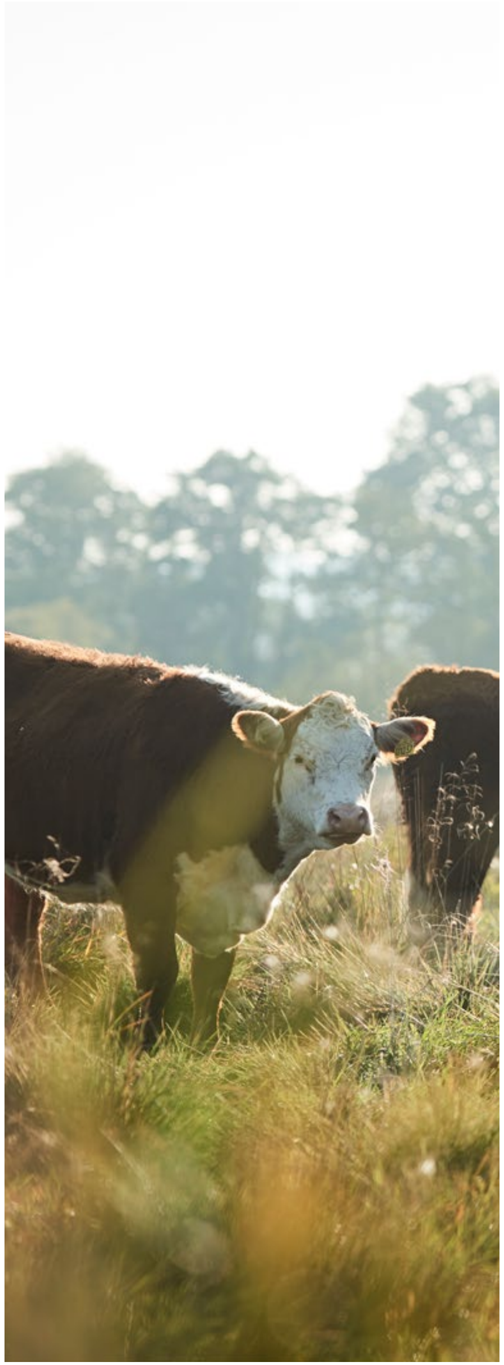
"A European standard for certification of carbon removal is on the way, and it could strengthen the market for purchases and sales of carbon removal certificates."
- The CIP Foundation

If, in the current negotiations, the EU can classify biochar as a climate measure with long-term and stable storage effects similar to other CO_2 storage technologies, such as DACCS and BECCS, this will give an important signal to the market.

CLEAR SIGNALS FROM INTERNATIONAL REGULATION

In 2018, the UN Intergovernmental Panel on Climate Change (IPCC) decided to recognise biochar as a Net Zero Emissions technology, and the panel has subsequently estimated a global reduction potential of 2.6 bn. tonnes CO_2e annually. In other words, there is a need for a broad range of CCS technologies, if we are to limit the rise of global temperatures. A need to both capture emissions from hard-to-abate industries, but also to capture previous CO_2 emissions from the atmosphere.

In 2022, the EU allowed biochar based on plant residues to be used in the EU as fertiliser for the first time, and later also biochar based on livestock manure via the revised Fertilising Products Regulation. Now biochar fertilisers may be sold within the EU if they are CE labelled and meet certain content requirements.



BIOCHAR IS ALMOST NON-EXISTENT IN DANISH REGULATION

In the summer of 2023, biochar made from agricultural residues was incorporated as a fertiliser product in Danish regulations for the first time. But only in regulations around how to use it, not a general permission to spread biochar on fields.

Broadly speaking, is the use of biochar based on agricultural residues not legally allowed in Denmark. A special environmental permit is required. More specifically, a section 19 approval ("§19 tilladelse") from the municipality. The permit is temporary and only applies for specific fields and specific amounts of biochar. This type of permit is used when there is no other regulation. It is impossible to base market deployment on this.

Regulations on biochar in Denmark have to be derived indirectly through other regulations. Because of that, paradoxically, Danish regulation allows biochar based on waste such as sewage sludge to be spread on fields. This is one of the feedstock types that might contain the highest amount of substances of concern. Therefore, only some biochar can currently be used in Denmark.

Paradox: biochar based on waste is allowed in Denmark, while biochar based on cleaner feedstock such as straw residues or grass requires a special environmental permit.

NEED FOR CLEAR FRAMEWORK CONDITIONS

The absence of direct regulation of biochar is a source of uncertainty and an obstacle to market development.

The same applies for rules on locating pyrolysis plants, as these often require time-consuming changes to local development plans, etc. In this context, the experiences from the construction of the biogas market serves as an example to be studied, and pyrolysis plants should be allowed to be sited in rural zones as well.

Socio-economic costs of storing one tonne of CO_2e:

Biochar from straw	DKK 250
Biochar from biogas fibres	DKK 700
BECCS	DKK 1,450
DACCS	DKK 1,500

If potential environmental impacts and income from climate credits are also taken into account, biochar has a socio-economic gain, while BECCS remains a cost.

Source: EA Energy analyses (2024)

Major investment decisions on market deployment are unlikely to be made, when permitting and local approvals are associated with much uncertainty and with the risk of local variations.

"There is a need for clear framework conditions and particularly for a clear legal basis on the use of biochar on Danish fields, provided compliance with the limit values for the biochar's content."
- The CIP Foundation

As biochar can be produced from different types of feedstock residues, legal permission to use biochar on Danish fields should be independent of the type of biomass used in production. Instead, there should be regulation on the final content of the biochar. This will ensure that regulation is simple and unambiguous.

RISK OF NEGATIVE IMPACTS CAN BE PREVENTED

Since biochar is new to agriculture, extra effort should be put into preventing potential adverse environmental and sustainability impacts. For example, this could be when setting limits for the content of different substances in the biochar. It is important to apply a prudence principle based on the most restrictive existing limit values across fertiliser products, EU regulation, and requirements for different carbon removal certificates.
This is not because any negative impacts have been demonstrated from biochar use in agriculture, but so there is confidence in its use. Regulation for biochar should not necessarily be less restrictive than for other fertilisers, yet nothing indicates a need for tightened restrictions on the use of biochar as a fertiliser.

Continued research and knowledge-building from practice is required. The knowledge should systematised and form the basis for guidelines on the use of biochar.
Then a market can be established and followed by research experiments and measurements that can guide future development of regulations.

COMPETITIVE CO_2 STORAGE WITH BIOCHAR

From a macro-economic perspective, the cost of storing one tonne of CO_2 from the atmosphere using biochar is competitive with other CCS technologies such as DACCS and BECCS.

Biochar is therefore an effective and relatively inexpensive way for society to achieve climate improvements compared with other climate measures.

"From a socio-economic perspective, using biochar as a climate measure is associated with a relatively low displacement cost."
- The CIP Foundation

Taking into account some of the adverse environmental side-effects of the different methods, the net result in macro-economic terms is improved for biochar based on digestate, whereas it is worse for BECCS and largely neutral for biochar based on straw residues.

Taking the possibility of payment for the service derived from CO_2 storage into account, for example through climate credits, further changes the picture. The use of biochar ends up as a small gain for society, while BECCS remains a net socio-economic cost, although this method can also obtain financing through climate credits.

Including potential revenues from climate credits in the socio-economic calculation gives an impression of the extent government funded support required for this type of CCS. This may be required in a start-up period for the market, and while the international market for climate credits is under development, standardisation, and consolidation. However, in the longer term, there are prospects that carbon storage with biochar will be financially sustainable for society.

Biochar as a climate measure is a socio-economically good investment. And one of the few climate measures with such potential, particularly in agriculture. Therefore, promoting the market should be considered through clear regulation, effective approval processes, and through CCS subsidies during market start-up. This is to cover some of the costs of CO_2 storage, which potentially could be met by the market for climate credits once it is less uncertain.

RECOMMENDATIONS AND A PLAN FOR LARGE-SCALE PRODUCTION OF BIOCHAR
Biochar could potentially play a major role in the green transition of Danish agriculture. It is based on a mature technology, and biochar can store large amounts of carbon effectively for up to 1,000 years. Furthermore, the socio-economic abatement costs of carbon sequestration with biochar are very competitive amongst other climate measures. In contrast to the large carbon-capture installations at CHP plants and large industrial enterprises, this type of carbon capture and storage can be decentral and close to where feedstock residues exist.

For agriculture as a whole, all the biochar stored in agricultural land will contribute to the total emission reduction requirement for agriculture. Even though climate credits are sold off to third-party companies, the net storage will still count in national and sector-based emission inventories.

"All reductions from using biochar in agriculture will reduce the collective requirements for agriculture as a whole – even if climate credits are sold, for example."
- The CIP Foundation

The collective gains in the form of reduced net emissions from agriculture therefore entail a corresponding reduction in the need for a carbon tax or other instruments aimed at agriculture.

Biochar has the potential to contribute to Denmark's 2030 targets, and the later goals of climate neutrality in 2045, and net negative emissions in 2050. Biochar cannot meet the political objective of 2 million tonnes of carbon storage by 2030 from the agreement on a green transition of the agricultural sector, as it is impossible to build such production capacity so rapidly. But it is likely within relatively few years after 2030, depending on the framework conditions.

Even though other countries have been making biochar for some time, they have not had climate impacts as their primary focus. Denmark has potential to develop a biochar industry in light of existing logistical opportunities for various types of biomass residues, possibilities to sell green energy and surplus heat through well-developed infrastructure, and possibilities for co/localisations.
Technologically, Denmark is also up to speed, and at the beginning of 2024, Denmark will have one of the largest biochar-production facilities in Europe. Other Danish producers are also underway with large, commercial installations.

So, there is a basis for biochar, the supporting technology, and effective documentation of the climate impacts to be a new Danish export stronghold. Export opportunities, competence building, and learning-effects are themes for the next initiatives by the CIP Foundation within this area.

The most important challenges right now in order to use this promising technology in Denmark are linked to the absence of direct regulation of biochar in Danish legislation, to new value chain collaborations where income must be obtained to cover the costs of carbon storage, and for an increased knowledge and practice of how biochar can be used.

On this basis, the CIP Foundation recommends the following:

The CIP Foundation's main recommendations

- **Establish a legal framework for the use of biochar made of agricultural residues**
- **Allow access to CCS subsidies on a competitive basis with other CDR technologies during the initial phase**
- **Develop guidelines for the use of biochar in agriculture**

***Tabel A**: Recommendations from the CIP Foundation to promote biochar as a means of carbon storage in agriculture*

	Regulator	Market players	Researchers and experts
Central recommendations	Establish a legal basis for biochar made of agricultural residues.	Support the start-up with CCS subsidies; to be replaced by the market for climate credits.	Develop guidelines for the use of biochar in agriculture.
General recommendations	• Start with **framework regulation** and **limit values** for the biochar contents, based on the strictest current limits across different regulation and by applying a prudence principle, which can be tightened or relaxed in line with new knowledge. • **Inter-ministerial task force** with focus on authorisation and process simplification for quicker establishment of biochar production. • Develop **method to calculate net CO_2 storage** with biochar in the national emission inventories, so that storage can also be recognised and included in political objectives. • **Identify relevant areas for pyrolysis plants** in combination with current municipal projects to identify suitable areas for biogas production and energy parks for quicker establishment.	• Spread **awareness among potential investors** to accelerate interest in the technology. • Establish logistics chains with the possibility of **long-term agreements** (PPPs) for biomass and biochar. • Accelerate **scaling and learning processes** to develop the pyrolysis technology to large-scale. • Start **development of energy products for high-value use** and prepare possible upgrading, methanation and future coordination with PtX.	• **Categorisation of research results** according to evidence, biomass, pyrolysis process and area of application to make insights more practicable. • Initiate **long-term field studies** and gain an overview of the long-term environmental and agronomic impacts of use on agricultural land. • Develop **practical knowledge** for optimal use of biochar and exchange experience. • Extend **competence development**, training activities and learning tools for the people who are to develop, operate and administrate/supervise etc. biochar processes.
Specific recommendations	• **Equate pyrolysis plants with biogas plants** in the Planning Act to support possible location close to residual biomass. • Support quicker **environmental classification** of pyrolysis plants and thus the process for environmental assessments with outset in standard examples. • Adjust **phosphorus caps** with regard to biochar-release over time. • Work to get carbon storage with biochar **in other sectors**, for example the construction sector, recognised in national emission inventories (via the IPCC). • Develop **standard processes** for municipal assessments and section 19 permits, until central regulation is in place. • Establish a "**compliance assessment body**" to approve biochar with CE labelling as a fertilizer product.	• Develop **field management methods** for biochar (agriculture and materials suppliers). • Develop **combination of biochar and other fertilizer products** to achieve the best effects.	• Investigate the impact of biochar on **nitrogen leaching** from soil to the aquatic environment. • Examine the **interplay** between biochar, soil type, and the effect of different types of living organisms in the soil under Danish conditions.

Source: The CIP Foundation

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At the CIP Foundation we conceive and implement long-term projects that support the transformation of Danish society towards a more sustainable future. We are an independent and non-profit organisation that delivers tangible and implementable solutions for a long-term transformation of Danish society.

For more information, visit cipfonden.dk

Glossary

BECCS — **Bioenergy with Carbon Capture and Storage**
Refers to a process in which biogenic CO_2 is collected from flue gas in a chimney (point source). After this, the biogenic CO_2 is stored underground in geological structures.

Biogenic CO_2 — is a term used to describe CO_2 from biological materials such as straw and sewage sludge.

Biochar — is a porous, carbon-containing product made from biomass residues that have undergone pyrolysis, and can be used to reduce greenhouse gas emissions from the biomass by storing carbon as a product with soil-improvement properties.

Biomass — **or feedstock**
is material from previously living organisms, e.g. wood residues, plant residues and other agricultural residues, as well as organic waste from households and industry.

CO_2 — **Carbon dioxide**
The most well-known greenhouse gas. It is composed of carbon and oxygen.

CO_2e — **CO_2-equivalents**
Unit of measurement used to compare the impact of different greenhouse gases such as methane and nitrous oxide that are more potent than CO_2.

CCS — **Carbon Capture and Storage**
Covers different carbon capture methods used to store CO_2 for a very long time, for example in the subsurface.

CCU — **Carbon Capture and Utilization**
Utilise captured carbon in other products and processes, e.g. for green fuels.

DACCS — **Direct Air Carbon Capture and Storage**
A technology, where CO_2 is extracted directly from the atmosphere.

Digestate — is the residual material (fibres and fluid) left after biogasification processing of biomass.

ETS — **Emission Trading Systems**
EU trading system for carbon allowances in which a limited number of allowances can be traded between businesses in the ETS sector (energy production, large industrial installations and aviation).

Phosphorus — is an essential nutrient (P) in fertilisers, for example. Phosphorus is a limited and non-renewable resource that is obtained through mining.

Fossil CO_2 — is a term for the CO_2 released when fossil fuels such as gas, oil and coal are burnt. There is no chemical difference between fossil CO_2 and biogenic CO_2.

Nitrous oxide — is a greenhouse gas (N_2O) and like CO_2 it contributes to global warming. It is 298 times as potent as CO_2 in relation to climate impacts.

LULUCF — LLUCF includes agricultural areas, nature areas and forests, etc.

Methane — is a greenhouse gas (CH_4) and like CO_2 it contributes to global warming. It is 25 times as potent as CO_2 in relation to climate impacts.

Net-zero — is when a company or a country reduces its emissions and overall does not emit more greenhouse gases than it compensates for through CO_2 removals.

PAHs — **Polycyclic Aromatic Hydrocarbons**
Tar compounds that can be formed during the pyrolysis process if the process is not under control and the biomass residues are "over-cooked".

PFAS — **Per- and polyFluoroAlkyl Substances**
Chemical fluorinated substances or "persistent chemicals", which can be found in waterproof clothing, kitchenware and paint, for example, due to their water-, dirt- and fat-resistant properties. PFOS is a subset of this group and has previously been used in fire-extinguisher foam.

PtX — **Power-to-X**
Covers technologies which produce fuels, chemicals, and materials on the basis of green hydrogen produced through electrolysis.

PyCCS — **Pyrogenic Carbon Capture and Storage**
Carbon capture and storage in biochar through pyrolytic treatment of biomass.

Pyrolysis — is a process in which a material (biomass) is heated to high temperatures without oxygen by which it is split into a gaseous fraction (pyrolysis gas) and a residue (biochar).

TRL — **Technology Readiness Index**
An index of how developed and commercially mature a technology is from 1-9. Pyrolysis is around 8 in the maturity scale.

Why carbon storage with biochar?

Chapter 1

When you make biochar from biomass residues, you get not only a material for storing carbon; you also get green energy, and product with many uses, for example as a fertiliser in agriculture. It is not very well known, but it has huge potentials, and is ready for commercialisation, if the right framework is established.

1.1. What on earth is biochar?

In recent years, biochar has received increasing attention as a potential sustainable solution to several challenges: the need for green energy, for climate change mitigation, and for environmental improvement.

Biochar can store carbon stably and for a very long time. And if you for example use it as a feritiliser there are a number of positive side-effects. Moreover, green energy is generated in the process of making biochar.

Biochar is not like fossil-based coal, which is still used to fuel many power plants and companies around the world. Biochar is made from residues from plants that have absorbed CO_2 from the atmosphere. When the plant residues go through the pyrolysis process, the carbon is stabilised in the biochar.

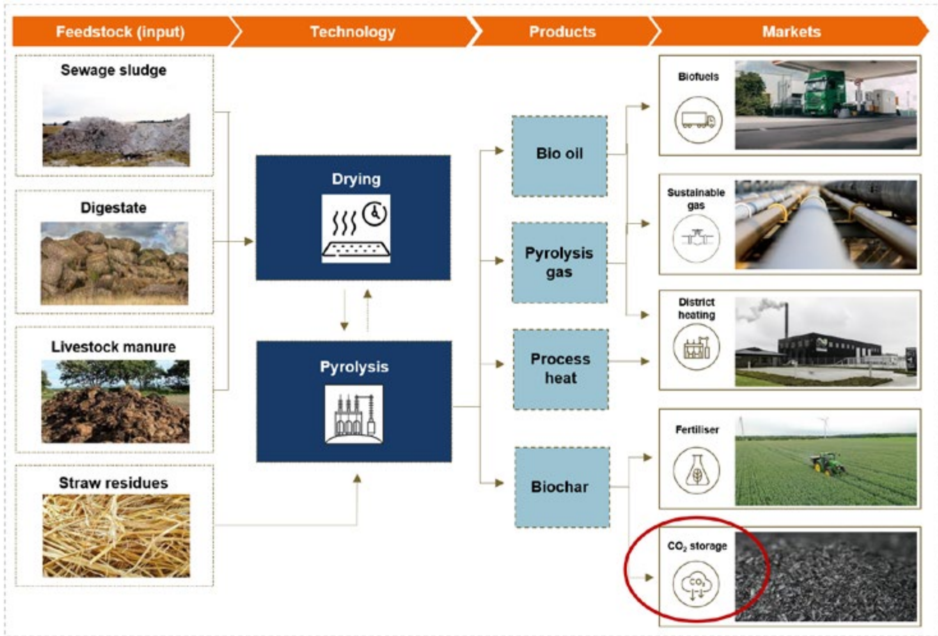
RESIDUAL PRODUCT STORES CARBON
Biochar is the residual product that remains after biomass residues such as straw, sludge, manure, or wood chips have been treated at high temperature (without oxygen) in a pyrolysis plant. The process also produces green energy in the form of pyrolysis gas and bio-oil (depending on the process and the energy in the biomass). The pyrolysis process produces more energy with the biomass than it uses during the drying and heating process. Furthermore, there is surplus heat that can be used to dry biomass residues or can be sold as district heating. See illustration of the process in figure 1.1.

Around half of the carbon from the biomass ends in the biochar, and the other half ends in the pyrolysis gas and bio-oil which also come out of the process.

Because it can store the sequestered carbon from biomass stably and for a long period, biochar can help reduce the amount of carbon in the atmosphere and, thus, help mitigate climate change. This makes biochar a valuable climate measure. Both for storing "old" emissions and for helping in areas where it is hard to reduce emissions to zero. For example, carbon emissions from livestock and farmland.

EMISSIONS FROM FOOD PRODUCTION CAN BE NEUTRALIZED THROUGH CARBON STORAGE
Agriculture accounts for a considerable proportion of greenhouse gas emissions. Up to 30% in Denmark in 2022 (including nurseries)[1] and around 35% globally[2]. In contrast to other industries, emissions from agriculture are largely related to natural processes. Furthermore, a growing global population means that there is still a great need for food production. But even if food production is transformed and becomes more climate-friendly, there will always be emissions from producing food.

***Figure 1.1:** The process behind biochar and CO_2 storage in agricultural land*



Source: The CIP Foundation's own graphic

Many solutions have to be implemented, the emissions must be reduced, and carbon must be captured and stored. Biochar is not the only solution. But it has great potential. The market for biochar is in its infancy, and the technology is being developed on virtually all continents: China, the USA, and several places in Europe, including Germany and Sweden.

Despite being a little late in starting biochar production, Denmark could build a strong position in the biochar market relatively quickly. However, there are significant barriers to biochar in a Danish context.

1 Statistics Denmark, DRIVHUS, for the year 2022 for the sector Agriculture and Horticulture.
2 Videnskab.dk (2021)

Identifying and understanding these barriers is crucial in order to develop effective strategies to overcome them.

In this report, the CIP Foundation will describe the possibilities of commercialising biochar production and carbon storage in Denmark for use in agriculture and potentially elsewhere.

The report focuses on relevant biomasses for biochar, areas of application, possible co-benefits, profitability in production, opportunities to charge payment for carbon storage, regulatory challenges, relevant value chains, societal effects and the macro-economics behind biochar compared with other climate measures.

1 tonne of biochar ~ 2 tonnes of carbon

What does one tonne of biochar correspond to in terms of climate?

- Manufacturing a car battery for the Tesla Model 3
- 33 round trip journeys by car from Aarhus to Copenhagen
- Almost 2 return flights from Copenhagen to Rome
- 13 kg beef tenderloin

Each Dane's consumption emits what corresponds to an average of 13 tonnes of CO_2e. This is the amount of carbon that 6 tonnes of biochar can store.

Sources: Se hvor stort dit CO2-udslip er, når du rejser | Green-Match, CONCITO (2023) and own calculations.

1.2. Biochar is a method of carbon capture and storage (CCS)

Biochar stores carbon stably and for a very long time because the carbon is tightly bonded and not broken down easily by organisms in the soil to release CO_2 again. Approximately three-quarters of the carbon content remains after 1,000 years. This permanence for example corresponds to when carbon is stored and mineralised in the North Sea. Read more in Chapter 3.

If the feedstock is not converted into biochar through the pyrolysis process, the carbon content will be released back into the atmosphere when the biomass for example is used as a mulch on fields. Therefore, biochar can help remove carbon from the atmosphere that would otherwise be released.

BIOCHAR IS THE FINAL STEP IN A CIRCULAR USE OF BIOMASS

The use of biomass for biochar is circular when the process utilises residues and side streams from agriculture and other industries that have no other use, and when the biochar is returned to agricultural soil to fertilise and feed new biomass. By using residues, the production of biochar does not take up land that could otherwise be used for other purposes. Neither does it require growing biomass with just the specific purpose of producing biochar. The biomass is a co-benefit from other processes.

BIOCHAR IS MAINLY USED IN AGRICULTURE, BUT HAS ADDITIONAL APPLICATIONS

Biochar is mainly used for fertilisers on farmland and for compost. Biochar also has other potential applications in a number of other sectors. Newer applications include uses

***Figure 1.2:** Examples of the use of biochar*

Source: The CIP Foundation's own graphic

in the construction industry and in a variety of different materials.

See figure 1.2 for examples of biochar applications.

1.3. Biochar could be a central element in the green transition

The process behind biochar provides both CCS and green energy. Green energy can lead to avoided emissions and displacement of emissions when surplus heat and bio-oil are used instead of fossil alternatives. Furthermore, biochar has a number of co-benefits for society: improved soil quality, improved water retention and reduced need for artificial fertilisers and pesticides. Read more in Chapter 3.

Biochar therefore represents a bridge between sustainable food production and soil protection. The pyrolysis technology used to produce biochar could potentially help agriculture become a net remover of carbon, thereby shifting its status from being one of the largest carbon emitters to being a mitigator of climate challenges. A benefit for agriculture as well as for society.

STRONG POLITICAL INTEREST IN BIOCHAR

Politically, the great potential of pyrolysis technology and biochar in the green transition has already been noticed, and several political steps have been taken to promote the market.

In the agreement on a green transition of the agricultural sector from October 2021 ("Aftale om grøn omstilling af dansk landbrug"), the Danish Parliament set a target that pyrolysis technology should annually contribute to the sequestration of 2 million tonnes of CO_2e in the agricultural sector from 2030. In addition, funds were earmarked to support technologies that can promote the transition in Danish agriculture up to 2024. Read more in Chapter 4.

The government will issue a pyrolysis strategy in early 2024. The strategy will revise the objectives and necessary initiatives will be renegotiated.

Many different climate measures can support Denmark in achieving its climate targets. Although biochar seems to store carbon relatively cheaply, all climate measures are required. Biochar cannot stand alone. Read more in Chapter 5.

1.4. Market under development

Compared to more established industries like traditional biomass energy from biogas or renewable energy, the biochar industry is in its infancy. The supply options are relatively restricted, and production capacity is still under development.

The first major commercial pyrolysis plant for biochar in Denmark will be inaugurated in early 2024. At European level, biochar is more widespread: approximately one-third of European production capacity was located in Germany in 2022, while a quarter was in the Nordic countries, and the remaining capacity was in Austria, Switzerland, etc. (EBI 2023).

In 2022, biochar was primarily used for soil improvement and as a fertiliser. Another, but less widespread use, is as an animal-feed additive and in electricity production (EBI 2023).

LACK OF REGULATION

The regulation around biochar is complex and spans across several authority areas in Denmark. Biochar only appears sporadically in Danish regulation due to its lack of use. Instead, biochar regulation is indirect through interpretation of other regulations with other purposes.

In summer 2022, the EU recognised biochar based on plant residues and livestock manure as a fertiliser product in the Fertilising Products Regulation. Danish regulation has followed suit, with regulations on how to use biochar as a fertiliser, but the legal basis for actual use remains uncertain. Today, it is generally not allowed to spread biochar from agricultural residues on Danish soil, as it requires a special permit obtained after assessment by the municipality.

1.5. What are we waiting for?

Biochar represents a sustainable way forward, with more green energy and simultaneous reductions in carbon emissions. So what are we waiting for? Despite the promising potentials of biochar and pyrolysis, several challenges need to be addressed.

When a new technology is to be scaled up and commercialised, a range of challenges may exist, from technological development to regulatory barriers, uncertainty about profitability and risks, and a lack of knowledge and awareness among potential investors.

Currently, there is no predictable reward for carbon capture and storage in agriculture. Relatively certain but high production costs are associated with the technology, and revenue streams are uncertain. The existing regulation does generally not allow for the use of biochar from agricultural side streams to be applied on Danish farmland. So even though the technology is ready, it is difficult to secure agreements with potential buyers and users before investment.

There is also a general lack of knowledge about the long-term consequences of using biochar on agricultural land when it is based on today's feedstock and technology. In some cases, the feedstock may contain substances of concern such as heavy metals and PFAS, and there is also a risk of tar substances forming during the pyrolysis process if production standards are not properly managed. Although pyrolysis removes many substances of concern from the biomass, the risk of unwanted substances ending up in the biochar must still be managed, and this could be through strict limit values and fixed test standards for the content of the biochar.

With this report and the underlying analyses, the CIP Foundation aims to increase the knowledge base around biochar and its climate-related possibilities, and to examine what it will take for biochar to be commercialised at an appropriate scale to benefit Denmark. And, in the long term, to benefit other countries as well.

Biochar is not the answer to all climate challenges. We still need to reduce our carbon emissions wherever possible, but we also need to store carbon. Many different climate measures will have to be implemented to reach the goals. Biochar is one of them, with huge potentials and several co-benefits.

Can carbon storage with biochar compete with other methods such as BECCS and DACCS?

There are different methods for capturing and storing carbon, each with its own properties, but all of them can store carbon for a very long time and irreversibly.

Biochar is most relevant for agriculture, which is often responsible for both the supply of biomass and the final storage. BECCS, on the other hand, is more relevant for large biomass-burning power plants, i.e. the energy sector. DACCS is industry-independent and can be located anywhere near good storage options in geological formations. Both biochar and BECCS are dependent on adequate quantities of biomass residues and are tied to the location of the biomass. DACCS is more flexible, although it is also more expensive.

To meet the Paris Agreement and keep temperature increases at a minimum, all relevant technologies will probably have to be exploited. CCS addresses past emissions and unavoidable emissions, thereby supplementing efforts to reduce emissions. The three technologies complement each other in climate efforts.

The extent to which each technology should be deployed depends on governments' willingness to pay (in the form of CCS subsidies) and the market (from sales of climate credits or higher product prices).

What are the challenges for biochar?

Chapter 2

Several factors need to come together before biochar is ready for commercialisation on a larger scale. The main barriers are related to uncertain regulatory frameworks, knowledge and awareness, while there is greater certainty about the technology, business case, and the socio-economic value of biochar and its associated positive climate impacts.

WHY IS BIOCHAR NOT ALREADY WIDESPREAD?

If it is such a good idea to store carbon with biochar in agriculture, then one could ask why it is not already happening at a large scale.

There are various reasons for why biochar is not widespread. When a new market needs to be established and function well, a number of "cogs" need to work together. The CIP Foundation believes that all the "cogs" in carbon storage with biochar are turning or have the potential to turn, but some are slower than others. There are solutions to this.

2.1. The technology

The technology behind biochar production is relatively mature, and several manufacturers in Denmark and abroad have been developing and producing pyrolysis plants for several years. For example, the German PYREG has been behind more than 50 different installations, and the company can scale production capabilities by connecting multiple standard units. Others make more site-specific solutions.

So far, focus in Denmark has largely been on pilot projects and testing and demonstration plants (TRL 5-6), and in 2022 the Pyrolysis Pool provided funding to scale up plants with focus on demonstrating production at commercial scale.

A new large-scale production plant (TRL 8) has recently been established in Denmark and is currently being tested. When it comes into full production, it will be among the largest in the world and will be able to produce more than 10% of the total current biochar output in Europe.

The next phase is continued scaling of Danish pyrolysis capacity and demonstrating stable operation. If the market is to be expanded, the technology must be reproducible in a standardised way. It must be possible to build multiple units which are not individually unique. Otherwise, the investment will become too demanding.

Over time, the technology will be continuously improved, and larger and more efficient plants will be able to manage larger amounts of biomass residues and produce more biochar with greater carbon storage capacity. The price of establishing pyrolysis production will fall, and the costs of storing carbon will be reduced.

The technological "cog" is therefore well on its way to market deployment.

Technology Readiness Level (TRL)

TRL 1: Basic research

TRL 2: Formulation of technological concept

TRL 3: Experimental proof of concept

TRL 4: Technology is tested and validated in a laboratory environment

TRL 5: Technology is tested and validated in a relevant environment

TRL 6: Technology is demonstrated in a relevant environment

TRL 7: Prototype is demonstrated in an operating/production environment

TRL 8: The technology/system is complete and fully developed at a commercial level

TRL 9: The technology/system is ready for full-scale production/operatation

Source: The Innovation Fund and the Danish Agency for Agriculture's GUDP guide

***Figure 2.1:** Several types of challenges for the biochar market*

Source: The CIP Foundation's own graphic

2.2. Feedstock

Another crucial "cog" for the market is whether there are enough relevant and financially viable input factors for biochar in the form of biomass residues. And whether the biomass is located reasonably close to potential sites for pyrolysis plants and are logistically manageable.

Biochar can be generated from a wide range of different types of biomass, and it can be based on residues that do not have any other significant economic use, having reached the end of their circular use. In other words, residues at the bottom of a cascade of biomass uses, such as residual fibres from biogas plants, residues from green biorefining and from food production, hay residues and straw residues from catch crops, livestock manure, garden waste and even sewage sludge.

Virtually any biomass residues imaginable will contain carbon and can be pyrolysed.

Important factors in determining the optimal location and size of biochar production plants include the specific biomass, the price, the scale, the possibilities of stable delivery over time and the logistics. The most obvious biomass residues for pyrolysis will be locally determined by transportation considerations and are decisive for the size of the installation.

There is competition for biomass, including biomass side streams, and, among other things, future development opportunities depend on the future agricultural area, the crops cultivated, and the designated land uses.

NIRAS (2023) has mapped selected biomasses relevant for pyrolysis and has concluded that there are currently enough biomass residues to produce biochar corresponding to 2 million tonnes of carbon storage annually. Furthermore, Det Nationale Bioøkonomipanel (2022) has analysed a range of biomass scenarios and concluded that there is potential to increase the amount of biomass by up to 10 million tonnes of dry matter in 2030 with relatively simple measures. Because a multitude of different biomass side streams can be used for biochar, and because there are different growth opportunities for biomass, even if overall agricultural production is reduced, there is still a good and flexible foundation for carbon storage based on biochar in Denmark. However, the individual business case for biochar production will depend on the local supply of biomass residues and the opportunities to secure a stable supply.

The "cog" for biochar production input is therefore fairly well lubricated but may have local variations.

See Chapter 3, #2, for a more detailed description of relevant biomasses and NIRAS (2023) for an in-depth analysis of relevant biomasses for carbon storage with biochar.

2.3. Payment for carbon storage

Implementing carbon capture and storage based on biomass residues is associated with costs, but there are also potential revenues, especially from sales of the green energy produced in the same process. However, as shown in Chapter 4, revenues will not cover the costs of the overall carbon storage process.

The business model assumes that there is some form of financial reward for storing the carbon. For example, this could be revenues from sales of carbon removal certificates, i.e. where buyers pay for the carbon storage in order to use the climate impact in their own climate accounts. Financial reward may also be through a higher consumer willingness to pay for climate-friendly products from farmers who have contributed to carbon storage. Or it could be through state support similar to that provided for other CCS technologies.

A market-driven "cog" will depend on the voluntary market for climate credits providing adequate compensation for the costs of carbon storage.

See the description of climate credits in Chapter 3, #5, and in SEGES Innovation (2023).

2.4. Demand for biochar

Even if there is willingness to pay for carbon storage with biochar, biochar must also have obvious uses that can guarantee stable storage.

In other words, biochar must offer uses with known final destinations and reliable long-term storage. For example, if applied to soil, biochar will remain in the soil and cannot be collected again, and the same applies if it is mixed with materials such as cement, composite materials or asphalt.

If someone wants to invest in carbon storage, they will purchase it through a carbon removal certificate for example, corresponding to the capture and storage of 1 tonne of carbon. This is likely not the same person who is looking to buy biochar as a physical product.

The carbon removal certificate for carbon storage is attractive for companies that want to include it in their climate footprint or the climate footprint of their products. That is, for marketing purposes.
Those who want biochar for its utility value may require it for its fertiliser value and soil-improvement properties. Or for its ability to absorb and retain substances of concern (soil remediation or filtration).
In other countries, the use of biochar in agriculture, and as a garden/park fertiliser in particular, has been the focus of attention from the start. The more uses there are, and the more reliable the carbon storage, the larger the market.
The overall market for biochar is still relatively limited, and increased marketisation will also require an understanding of the biochar's utility value and where it can be used. It requires knowledge about the effects of use and familiarity with biochar as a product. This "cog" is starting to turn little by little.

> *But what if toxic substances form during the pyrolysis process?*
>
> *In general, the biochar will not contain any substances, etc. that were not already there in the original biomass - only the concentrations will change. In fact, there will be fewer substances of concern because pyrolysis burns off microplastics, medicine residues, pesticides, etc.*
>
> *During the pyrolysis process, there is a risk that tar substances (PAH) will form, but this can be controlled with standardised production methods for temperature and production time. In addition, each batch of biochar produced can be tested for contents of undesirable substances, such as heavy metals, above certain threshold values. It is therefore possible to control the permitted content by applying reasonable limit values.*

The demand for biochar depends on demand for its positive climate impact and demand for its use for something specific. And, finally, it depends on what it costs to produce.

This is where the regulatory framework comes into play. It must be clear what biochar can be used for. Being able to sell biochar is clearly an important requirement if anyone is to start producing it.

Learn more about the profitability of biochar in Chapter 4, the potential marketisation of biochar in SEGES Innovation (2023), and what other countries are doing in Chapter 8 and in the CIP Foundation's background report (2024e) (in Danish).

2.5. Regulation and framework conditions

The possibilities for a new market also depend on the framework conditions under which the market will operate and the type of regulation that prevails.

In summer 2022, biochar was recognised by the EU as an agricultural fertiliser that can be sold within the EU if it complies with a specific labelling scheme. National regulations, however, may restrict the possibilities.

Currently, one of the biggest challenges to the use of biochar in agriculture in Denmark is that there is no legal basis for using it if it is made from agricultural side streams; there is only a legal basis if it is made from waste. Danish regulation of biochar is instead indirect through local decisions on the biomass residues selected as input, and through temporary, site-specific environmental approvals. It is not a transparent regulation. And this is not conducive to a market where political ambitions are growing rapidly.

In the establishment phase of pyrolysis plants too, there are various forms of “delay” in the framework conditions because the regulation does not specifically address biochar and pyrolysis plants. What is allowed and not allowed is up to interpretation by local authorities. This is very time consuming. It places high demands on competencies and administrative resources in municipalities.

The regulatory "cog" is among the more sluggish for marketisation.

See further description in Chapter 6 and in the CIP Foundation's background report on regulation and framework conditions (CIP Foundation, 2024a) (in Danish).

2.6. Value for society

Climate policy instruments are often compared on their socio-economic "shadow price", which indicates the net cost to society of removing 1 tonne of CO_2e with a specific instrument, after taking into account other consequences of its use (side-effects).

In this context, biochar as a storage technology is socio-economically competitive with Direct Air Capture with Carbon Storage (DACCS) and bioenergy with carbon capture and storage (BECCS) with storage underground.
The business case behind biochar for private players is highly dependent on the reward for carbon capture and thus on the market for sales of climate credits. And on energy prices.

After taking into account possible side-effects (both gains and losses) from a societal perspective, biochar based on biogas residues in particular will be a gain, because the process also prevents a number of emissions. For biochar made from plant residues, which result in the production of more green energy, the displacement of fossil-based energy will be a benefit, especially in a global context. A favourable socio-economic price can also have an impact on political interest in promoting the measure and establishing relevant framework conditions.

See Chapter 5 and EA Energy Analyses (2024) for more information.

2.7. Research and knowledge

Intensive research is being conducted into biochar and its effects, and the volume of literature on the subject is growing almost exponentially. The knowledge-based "cog" is turning and generating insight.

However, much is still unknown, and even though biochar has been used as a soil-improving agent for several hundred years in the Amazon, for example, we still need to know more about the long-term implications of using biochar.

Therefore, it is vital to carry out relevant trials and follow up on the knowledge generated in parallel with establishment of a market.

How much biochar should be applied to fields? How frequently? What are the effects with regard to nitrate leaching from the soil? What are the potential risks, and how do they relate to the type of biomass used, soil type, etc.?

There are a lot of questions, and the answers should be collected according to the relevant level of evidence, the specific biomasses used, the production method, and the type of soil the biochar is used on. This will make it easier to manoeuvre between the desired impacts and what to avoid.

It is important that research knowledge is categorised and translated into user guides. Because biochar is not just biochar. Many of the side-effects depend on the type of biomass used, the method of production, and the soil on which the biochar is applied. As new knowledge is generated, the regulations can also be amended. So, the research-based and knowledge-based “cogs" are turning, but they need continued lubrication.

2.8. Awareness and acceptance

One thing is research-based knowledge. Another is general awareness, growing experience and practical knowledge.

Biochar and the possibilities for carbon storage are not so well known. Not by the public, nor by the potential investors, the potential users of biochar or the buyers of green energy and climate credits. It is important to spread knowledge about this form of carbon storage and establish a basis for understanding and acceptance. When something is new, there are likely to be misunderstandings and misconceptions.

This report addresses some of these misconceptions, and Chapter 3 provides answers to a number of common questions about biochar. Awareness can be spread through political focus and communication, knowledge-sharing, networking, drawing up guides, and by finding new ways of bringing knowledge into play. And through clarifying opportunities and shedding light on the challenges so that they can be managed.

Knowledge Synthesis on Biochar in Danish Agriculture from Aarhus University is a good example of a useful reference work, and with the rate at which research is being generated in this field, there is an ongoing need for reviews and popular dissemination of the knowledge obtained. There is a need to develop guidelines, exchange experience, and stimulate practice-oriented innovation. And for competence development.

There must be quality and documentation behind the communication to secure credibility and a foundation for acceptance. For example, the interdisciplinary research project SIMPLY[3] aims to establish a road map to guide the deployment of biochar through increased knowledge.

The carbon storage aspects must be credible. There must be no double counting or greenwashing. Carbon storage cannot atone for our own emissions, but is it morally wrong to trade in climate impacts? Some people may think so.

However, such trade is going on every day in the EU's emissions trading system for industrial companies and it is a recognised method for achieving the most cost-effective solutions.

Carbon storage is not a solution so that people can be allowed to just sit back and do nothing to reduce their emissions. They must continue their reduction efforts. But not all emissions can be completely removed or avoided. And some things take time.
We have to clean up after years of historical emissions. So, carbon capture and storage is a necessary climate solution, although it is not sufficient on its own; it must go hand in hand with lowering our current and future emissions.
There must be confidence in the potential environmental effects and in the possible impacts on biodiversity. Sustainability is more than just positive climate impacts.

Misconceptions and uncertainty about potential risks can slow down market development and hinder this "cog".

Why should we waste the energy potential in biochar and spread it on fields in Denmark when they are digging up coal elsewhere? And given the high energy prices, isn't it better to burn the biochar rather than using it for storage?

Biochar is based on biogenic sources, while coal is fossil-based. Biochar is about carbon capture and storage, the possibility to recirculate nutrients from the biomass, and about green energy from the process, while coal is about a fossil energy source. The two things are not immediately connected, except that the need for carbon storage with biochar will keep on growing as long as others are burning fossil-based coal.

The process of producing biochar from biomass generates green energy, which can be sold. And the carbon storage in biochar also represents a value. Furthermore, the biochar itself can have value, depending on what it is used for. Biochar represents long-term sustainability. If we only want to use biomass for energy, we can burn it in heating plants, as we do today. Biochar can be made from biomass that has been used multiple times, such as residues from biogas plants.

3 5-P4 SIMPLY - INNO-CCUS

Questions and answers about biochar

Chapter 3
What is biochar and how does it help mitigate the climate challenge?

What is biochar, and how does it help mitigate the climate challenge?
Biochar is the charred remains of plants and other organic matter that has been heat-treated. Biochar is nothing new. It has been used to improve the soil for centuries. But it is new to consider biochar as one of the solutions to the climate challenge. It works because the CO_2 that plants have captured from the air throughout the growing season is stored stably for many hundreds of years in the biochar. If biochar is produced on a large scale, it can therefore contribute to removing CO_2 from the atmosphere.

Chapter 3 is structured as a series of questions and answers, and it elaborates on what biochar is, how it is produced, how it can be used to capture carbon through pyrolysis technology, as well as the positive and negative impacts of using biochar on farmland.

1. What is biochar and what can biochar be used for?
2. What can biochar be made from?
3. What are the climate impacts of producing biochar?
4. How long can carbon be stored?
5. How much biochar can we make?
6. What is a carbon removal certificate?
7. How can biochar help agriculture?
8. How does biochar affect the biodiversity?

#1 What is biochar and what can biochar be used for?

Biochar is the solid product left after treating various types of biomass residues in a pyrolysis plant. The process involves heating biomass residues from agriculture (such as straw residues or manure), industry, or sludge from wastewater treatment plants at high temperatures of several hundred degrees (e.g. 500-600°C) in an oxygen-free environment.

The pyrolysis process converts the biomass into biochar, which is the charred biomass residues, and into green gases, which can be used for heat or further processed into oil and, after adding hydrogen into biofuels, for example.

The biomass residues from surplus straw, for example, contain plant residues that have removed CO_2 from the atmosphere through photosynthesis during the growing season and converted it into carbon. Approximately half of the carbon from the biomass is stored stably in the biochar through the pyrolysis process, while the other half ends up in the green gases.

Biochar stores carbon for a very long time and can be used as a fertiliser or for soil improvement by helping retain nutrients in the soil and slowing down nitrogen leaching, thus benefiting the aquatic environment. The fertiliser value of biochar lies in the fact that it contains nutrients such as phosphorus and potassium, which are recirculated back into the soil from the original biomass.

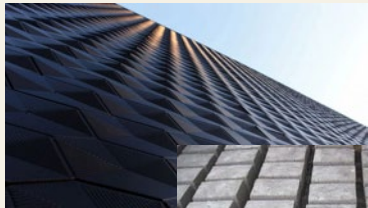
If the biomass is not converted into biochar, the carbon content will be released back into the atmosphere, for example when the biomass is used as a mulch on fields. Therefore, biochar can help remove carbon from the atmosphere and store it for hundreds of years if it is ploughed into the fields.

Biochar is currently primarily used as a fertiliser product for soil improvement in agriculture and for gardens/parks. In other countries, biochar is also used as an animal-feed additive, for example. Biochar can also be used in building materials (asphalt, concrete, panels, etc.)

Biochar can also be used for other niche purposes such as thermal insulation in clothing, health products, and protection against electromagnetic radiation in microwaves, TVs, power supplies, etc.

Read more about this in:

- Knowledge synthesis on biochar in Danish agriculture from Aarhus University →
- Tobias Pape Thomsen, RUC-IMT (2022) prepared for Food & Bio Cluster Denmark: Introduction to Production and Use of Biochar 2022 →




#2 What can biochar be made from?

Biochar is made from biomass residues from agriculture, industry, households, etc.

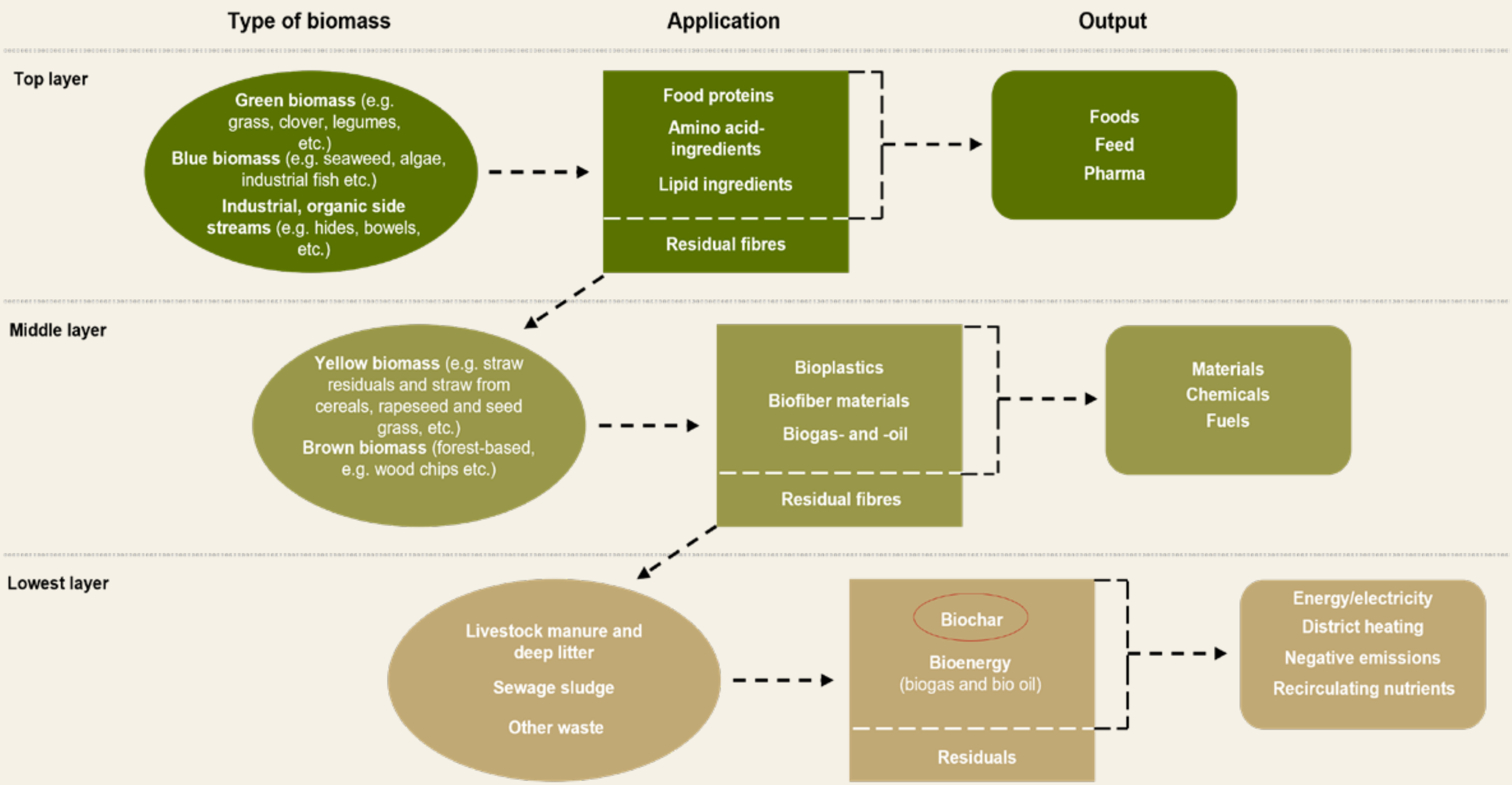
Biochar is the last phase in a circular use of biomass, and it is based on residues with no appreciable marketable value at the bottom of a cascade use of the biomasses. See also figure 3.1. Biomass residues can come from un-gathered hay and straw residues from other crops, sewage sludge, digestate from biogas plants, grass residues, grain from breweries, wood residues, waste wood from forestry and timber production, food waste, residues from the sea and garden/park waste.

The properties of the biochar depend on the type of biomass fed into a pyrolysis plant, and the temperature in the plant. The biomass used to manufacture biochar determines which regulation applies when the biochar is spread on the soil.

If biomass residues are not converted into biochar or bioenergy, the carbon content will be released into the atmosphere when the residues are stored and used as a mulch on fields, for example. When biomass residues are converted to biochar they get new value, because the pyrolysis process converts them into green energy and biochar (which can store the carbon stably), both of which can be sold.

The use of biomass residues in the pyrolysis process provides an incentive to collect more biomass (and thus more biogenic CO_2e).

***Figure 3.1:** Cascade use of biomasses, where they are prioritised according to purpose and use*



RELEVANT BIOMASSES IN DENMARK (EXAMPLES)

- Straw residuals
- Grass (including roadside grass, residues from biorefining of grass etc.)
- Other crop residues
- Livestock manure (e.g. from cattle, pigs and chickens)
- Deep straw bedding
- Digestate (residual fibres from biogas)
- Garden and park waste
- Wood waste and forestry residuals
- Seaweed and other marine residuals
- Slaughterhouse waste
- Grain residuals from breweries
- Food waste
- Sewage sludge
- Residuals from other processes (cf. cascade use)

Soruce: The CIP Foundation's own creation based on The National Bioeconomic Panel (2022) The Bioeconomic Panel report

#3 What are the climate impacts of producing biochar?

There are three overall types of climate impact related to biochar and its side-effects:
1. Carbon storage with biochar
2. Avoided emissions
3. Displacement effects

The size of the climate impacts depends on the type of biomass from which the biochar is made, and the alternative use of the biomass.

Carbon storage with biochar: Around half of the carbon content in the biomass ends up directly in the biochar where it is stored stably over time.

Avoided emissions: Processing the biomass instead of storing it, for example, prevents carbon emissions that would otherwise be sent into the atmosphere from the biomass. Preventing methane emissions is a particularly important climate impact.

Displacement effects: Biochar production also produces energy in the form of surplus heat from the heating process as well as pyrolysis gas and pyrolysis oils. The gas can be used for heating, while the oils can be further processed into green fuels. If the green energy replaces fossil-based energy sources, the climate will benefit from the fuel displacement effect from biochar production.

Overall, the manufacture of biochar has positive climate impacts, but only the carbon storage can be sold as a climate credit.

***Figure 3.2:** Climate effects of Danish manufactured biochar(100-year perspective)*

Feedstock (1 tonne dry matter)	CO_2e-storage in the biochar	Avoided emissions	Abatement benefit due to energy-surplus	Sum of the three climate effects
	Kg CO_2e per tonne of dry matter			
Straw	+610	0	+710	~ 1,300
Sewage sludge	+430	+600	+70	~ 1,100
Digestate	+620	+260	+680	~ 1,550

Source: The CIP Foundation based on Thomsen et al (2023) (2023)

#4 How long can carbon be stored?

Biochar stores carbon stably and for a very long time because it is not easily broken down by microorganisms in the soil. The biomasses used for biochar would otherwise decompose in their raw form over a few years and thus release carbon.

Across many studies and trials, researchers agree that around 80% of the carbon content is still retained in the biochar after 100 years. The permanence of the carbon has been described by a number of researchers in a joint statement published at the 2023 Biochar Summit in Helsingborg. Read their Joint Statement here.

However, it is very likely that biochar will retain its carbon content stably for significantly longer.
After 1,000 years, there is still about 75% of the carbon content left in the biochar, see Schmidt et al. (2022).

Recent geological studies indicate a much longer permanence for the remaining biochar, approaching the nature of "inertinite", see e.g. Sanei et al. (2024).

Such stability or permanence is almost the same as when carbon is stored in the subsurface, where it mineralises. So, biochar stores a large part of the carbon for a very long time.

Figure 3.3 shows the net carbon stored when applying biochar from 1 tonne of biomass as a mulch compared with applying the raw biomass as a mulch. In the beginning, the raw biomass stores more carbon than the biochar. This is because some of the carbon ends up in the pyrolysis gas during the pyrolysis process. But already after a few years, the biochar "overtakes" the original biomass as a carbon store and relatively quickly achieves the long-term storage effect.

***Figure 3.3:** Biochar stores more carbon than the alternatives already with-in 2 years*

Note: The figure shows the net storage of biochar minus the reference situation for the specific biomass.
Source: The CIP Foundation based on Thomsen et al (2023)

#5 How much biochar can we make?

The potential production of biochar and the resultant carbon storage depends on production capacity and on the amount of biomass residues available.

The CIP Foundation asked NIRAS (2023) to examine examples of relevant biomass residues, their scope, their potential for carbon storage and their geographical location in Denmark. On this basis, figure 3.5 shows selected, unused biomass residues in Denmark in relation to their scope and carbon content.

Some biomass residues are wetter than others, and therefore there are significantly smaller volumes of dry matter available, for example when digestate and sewage sludge is used. Dry biomasses can be transported more easily and over longer distances.

If biomass residues are not converted into biochar or bioenergy, the carbon content will be released into the atmosphere when the residues are stored and used as a mulch on fields, for example. When biomass residues are converted to biochar they get new value, because the pyrolysis process converts them into green energy and biochar (which can store the carbon stably), both of which can be sold.

The carbon content in biomass is equally divided between biochar and energy products. The amounts mentioned are an adequate basis for storage of 2 million tonnes of carbon, see figure 3.6. This corresponds to the political objective for biochar in the 2021 agreement on a green transition of the agricultural sector.

There is also the potential from other residues and the possibilities to increase the amount of biomass residues.

Det Nationale Bioøkonomipanel (2022) has assessed the different scenarios for future biomasses in Denmark and its uses.

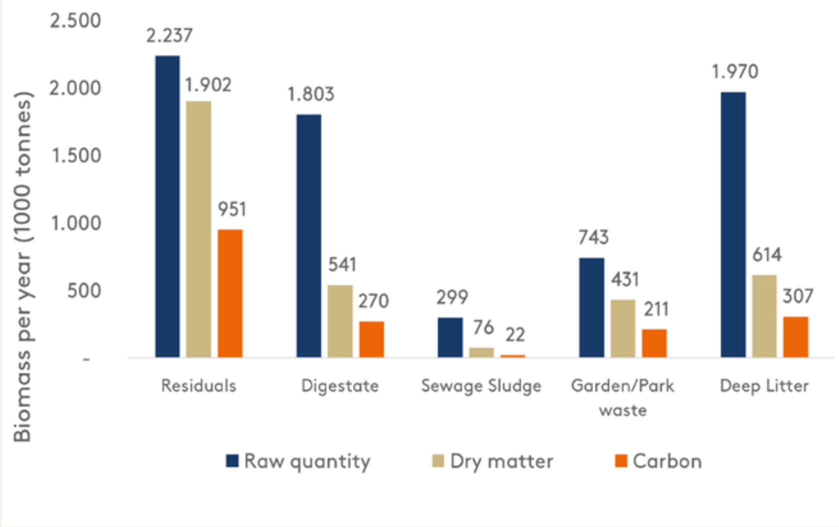
How land use is prioritised and the extent of livestock farming in Denmark will determine how much is grown, and thus the resulting volume of biomass residues.

The panel concluded that there is potential to increase the volume of biomasses up to 2030 by an amount corresponding to 10 million tonnes dry matter. Primarily in the form of more residual straw and hay. The increased volumes could come from growing more catch crops, for example, and using crops with longer straw and more chaff.

Part of this potential to increase the amounts of biomass will be relevant for pyrolysis. As a rule of thumb, 1 tonne of dry matter biomass can give 1 tonne of biochar and potentially 2 tonnes of carbon sequestration.

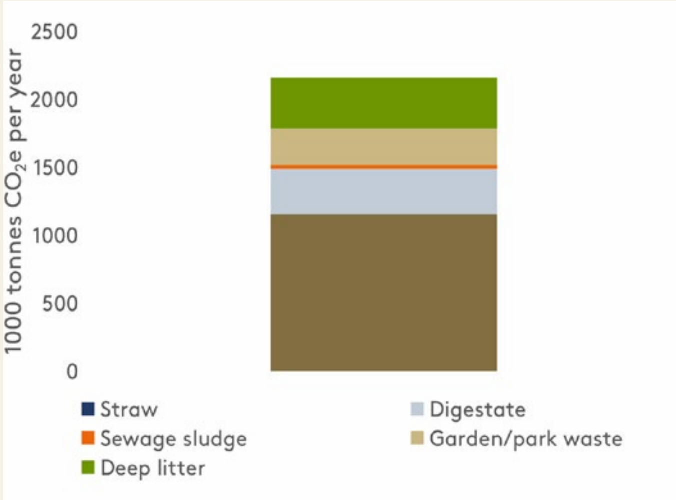
Even though biomasses can change over time, there are more biomass types relevant for pyrolysis than are included in the analyses shown, and it is possible to increase the amount of biomass residues over time. Therefore, it has been estimated that there will continue to be enough biomass residues in Denmark to support carbon storage corresponding to the political objective.

Figure 3.4: *Amount of selected, relevant residual biomasses for biochar*



Source: NIRAS (2023)

Figure 3.5: *How much carbon storage can the biomass support?*



Note: The carbon content is calculated after 100 years. The immediate carbon storage is higher.
Source: NIRAS (2023)

#6 What is a carbon removal certificate and a climate credit?

A carbon removal certificate is a commitment or proof of a reduction of climate-gas emissions or long-term carbon storage in a specific place in the world. A carbon removal certificate usually corresponds to storage of 1 tonne of CO_2e. If a carbon removal certificate is sold to another party, for example a party aiming to compensate for their own emissions, it is called a climate credit.

Climate credits are sold on a voluntary market, and they can only refer to new and additional measures. There may be different calculation methods and standards, depending on the platform the climate credit is sold from.

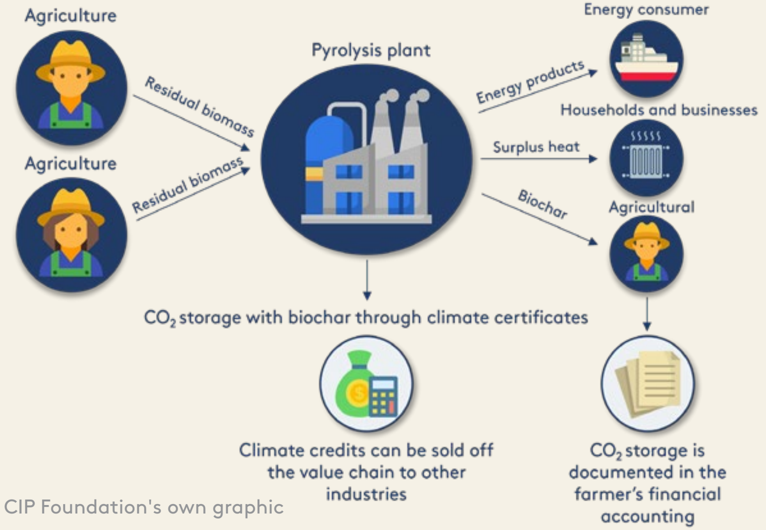
When producing biochar, the pyrolysis plant can issue carbon removal certificates to be sold as climate credits.

Sales of climate credits will finance part of the pyrolysis process and the subsequent carbon storage.
The voluntary market for climate credits is in significant development, driven by increasing demand for products and services with a reduced climate footprint, and by corporate climate targets.

In November 2022, the European Commission initiated work on a common certification framework for carbon removal by storing carbon in the soil or in forests, for example. A common certification framework will increase the credibility of European climate credits and make them more attractive to buyers.

Read more about the market for climate credits in an analysis from SEGES Innovation prepared for the CIP Foundation here.

***Figure 3.6:** Production of biochar can be financed through the sale of climate credits*



Source: The CIP Foundation's own graphic

#7 How can biochar help agriculture?

Agriculture and food production account for a considerable proportion of greenhouse gas emissions in Denmark. In contrast to other industries, climate emissions from agriculture are largely based on natural processes that require new solutions.

Today, several biomass residues in agriculture end up as mulch in the soil, e.g. surplus straw, livestock manure and deep litter. As the biomass residues rot in the soil, the carbon content in the biomass is emitted into the atmosphere. If the biomass residues from agriculture are processed by pyrolysis instead, large amounts of the carbon content in the biomass will be bound in the biochar. This means the carbon is not released into the atmosphere, and the climate impacts from agricultural biomass residues are reduced. Using biochar the carbon will be bound in the soil instead.

Everything else being equal, pyrolysis technology and biochar have potential to make agriculture a net carbon remover. This will change the status of agriculture from being one of the largest carbon emitters to being a mitigator of climate challenges, not only for the industry itself, but also at society level.

Carbon storage with biochar represents a possible path to new revenue flows for the individual farm which can be invested in other climate initiatives and/or pay a new carbon tax. The new revenues arise when the biochar production collects and pays for biomass residues which may otherwise have no significant economic value, and because there is a contribution to carbon storage by spreading biochar on the fields.

The revenue flows depend on selling a climate credit or in some other way obtaining payment for carbon storage, for example through a subsidy.

In addition to carbon capture and new revenue-generating opportunities, biochar also entails possible spin-off benefits in soil improvement and remediation of environmentally harmful substances.

Any carbon storage by agriculture will also benefit agriculture all at once since it will reduce overall requirements to reduce agricultural emissions. So overall, it may be an advantage for the individual farm to join the value chain around biochar.

Read more about this in:

- Knowledge synthesis on biochar in Danish agriculture from Aarhus University →
- The CIP Foundation background report on the potential environmental impacts (2024c) →
- The CIP Foundation background report on supply chains (2024d) → and Chapter 7
- The CIP Foundation background report on CO_2 taxes in agriculture (2024b) →

#8 How does biochar affect the biodiversity?

THERE ARE PRIMARILY POSITIVE EFFECTS FOR BIODIVERSITY
One quarter of the Earth's natural biodiversity is in the soil[4]. When biochar is used on agricultural land, it is therefore important to consider the implications of biochar for biodiversity.

The use of biomasses for biochar is not in itself a problem if the biochar is made from residues originally made for other purposes. In this way, production of biomass for biochar does not take up new farmland and does not involve land that could otherwise be used to benefit biodiversity. Pyrolysis and biochar are the "final call" on biomass residues originally cultivated for other purposes.

BIOMASS TAKEN FROM THE SOIL
A special consideration applies for biomass residues which could otherwise have been useful for the soil. For example, not all straw residues are collected from fields but are often left as a mulch instead. The uncollected straw residues may not have much economic value outside the farm, but they have an effect on the soil when it is mulched. Collection of straw residues will remove organic material from the soil. The net effect depends on what happens instead.

For example, if the straw residues are sold for heat production and incinerated, there is no recirculation of nutrients to the soil. Nor is there recirculation of important plant and crop nutrients, such as phosphorus. So, the soil may require other fertiliser input.

If the straw residues are sold for biochar production, some of the nutrients can be returned to the soil with the biochar and supplemented by other fertilisers, if necessary. However, there will be some delay. See, for example, EA Energy Analyses (2024) for a quantification of this side-effect on soil fertility.

Future use of straw residues for biochar should be based on continued use of some straw residues as mulch on fields. However, there are more uncollected straw residues than are needed. See, for example, NIRAS (2023). And as more catch crops are grown, the same field will also produce more straw residues, some of which will be relevant for biochar production, green energy, and carbon storage that is more permanent than if the biomass is used as mulch.

SOIL IMPROVEMENT AND INCREASED MICROBIAL ACTIVITY
The positive spin-off benefits of using biochar on agricultural land are related to soil improvement, in which, for example, biochar can influence the soil's calcium and phosphorous levels and enhance the water-retention properties of the soil, which may be an advantage in sandy soils and soils exposed to periods of drought.

Biochar may also help to reduce nitrogen leaching to nearby wetlands.
With its porous structure, biochar will also create more space in the soil for microbial activity and growth of plants' root systems, with consequent benefits for biodiversity in the soil.

Biochar will also increase the carbon reserve in the soil, which is otherwise declining in Danish soil.

Overall biochar will have a positive impact on soil micro-organisms, with a greater volume of microbial biomass, more diversity and more activity, see the Knowledge Synthesis on Biochar in Danish Agriculture from Aarhus University. But our understanding of the interaction between biochar, soil type and response is still limited, and there is a need for more research in the area.

When biochar is spread on farmland, it can affect biodiversity directly and through effects on the soil, depending on how much is spread, the type of biochar and the quality of the soil.

Biochar can therefore affect biodiversity through its effects on agricultural soil, primarily positive effects, but also potentially negative impacts, in particular at very high doses.

Read more about this in:

- Knowledge synthesis on biochar in Danish agriculture from Aarhus University →
- The CIP Foundation background report on the potential environmental impacts

4 EU Commission (2021) based on FAO (2020)

Want to learn more about biochar?

Read more on the CIP Foundation website here.

The CIP Foundation website has more information about the biochar project and relevant analyses, for example from NIRAS, Aarhus University, EA Energy Analyses, SEGES Innovation, etc.

There are also answers to various questions in the CIP Foundation's Q&A on biochar (in Danish).

Furthermore, there is information about the CIP Foundation's Advisory Board, which is linked to the biochar project and advises about the technical analyses for the project.

What is the business case behind biochar?

Chapter 4

It is financially viable for private actors to make biochar, for example from digestate and straw residues, and to store carbon with it, provided there are contributions from the sale of carbon removal certificates, from CCS subsidies or from higher consumer prices for more climate-friendly products.

4.1. What affects the price of carbon storage?

The total costs of carbon capture and storage with biochar range from initially obtaining biomass residues to treated them in a pyrolysis plant and subsequently applying the biochar and storing the carbon. The process involves several different players in all phases, from provision of biomass residues in agriculture, to industrial production of energy and biochar, subsequent sale to energy markets, and carbon storage, for example through spreading biochar on fields.

What affects the price of biochar?

- **Biomass** (e.g. price, logistics, need for pre-processing as well as energy and carbon content)
- **The pyrolysis technology** (construction and operating costs, capacity, efficiency, and energy balance)
- **Energy prices** (sales of different types of green energy)
- **Location of installations** (proximity to biomasses, sales of green energy, and synergies with other installations)
- **Carbon removal certificates** (costs of certification and price of climate credits)

The value chain is described in more details in Chapter 7.

There are revenues associated with the entire value chain behind carbon capture and storage. This is because, in addition to biochar, the pyrolysis process also generates heat and green energy in the form of pyrolysis gas, which can be used to produce heat, and bio-oil, which can be processed into green fuels.

DIFFERENT TYPES OF FEED-STOCK WITH DIFFERENT PRICES AND CONTENT

Some of the various biomass residues used to make biochar may be associated with costs if they have alternative economic uses: for example, straw residues can also go to incineration for heat. Others can be obtained for are almost free: for example, if a pyrolysis plant is sited close to another installation and de facto helps this installation dispose of residues it would otherwise have to deal with itself, for example a biogas plant having to deal with residual fibres. Furthermore, there are biomasses a pyrolysis plant can charge payment to receive, such as sewage sludge.

See Chapter 3, question #2, on relevant biomasses for production of biochar.

The very different biomass residues that could come into play have different compositions, and therefore also different characteristics when they become biochar. Some biomasses contain a relatively large amount of carbon that, with effective conversion, will affect possible earnings from carbon storage, while others contain relatively high volumes of phosphorus, and this may influence the fertiliser value of the biochar. See table 4.1 for the content of different biomasses. The biomasses also have different energy content, which will influence which set-up is profitable.

***Table 4.1:** Varying content of carbon and phosphorus depending on the choice of biomass*

Feedstock	Carbon (C)	Nitrogen (N)	Phosphorus (P)
Straw/grass	High	Low	Low
Sewage Sludge	Low	Medium	Medium
Digestate	Medium	Medium/high	High

Source: Knowledge synthesis on biochar from Aarhus University. Elsgaard et al (sept 2022)

MORE EFFICIENT PLANTS OVER TIME

Profitability of the total business case depends on the economic data of the pyrolysis plant, plant capacity and efficient energy recovery. Pyrolysis plants can have relatively high construction costs, and this has to be weighed against the potential earnings and the pay-back time. Plants are assumed to have a lifetime of around 20 years, but in practice they can be upgraded, and the lifetime can be extended. The business case should also take account of operating and maintenance costs.

Over time, it is likely that the technology will become more efficient, and that the plants can be reproduced and upscaled in such a way that costs per unit of biochar produced fall.

How the biomass is converted into energy (gas, heat and bio-oil) and biochar, respectively, can to some extent be adjusted by the pyrolysis technology (temperature and duration), and therefore the sales prospects for the energy and biochar are crucial.

With respect to the energy products, sales prospects relate to whether the pyrolysis gas and surplus heat can be sold to a district heating grid or other nearby undertakings. With respect to bio-oil, possibilities for further refining to green fuels and/or direct use are important.

HIGH ENERGY PRICES ENHANCE THE BUSINESS CASE

Energy prices have increased as a result of the current geopolitical turbulence, and for fossil energy products they will continue to rise structurally as a consequence of climate change and increasing CO_2 allowance prices.

Green energy from pyrolysis and biomass residues can help strengthen Denmark's energy supply and constitute a green alternative that does not depend on weather conditions such as sun or wind. It therefore fits in well with the future energy mix.

Using dry biomass residues as input is a particularly good case for producing green energy efficiently, and the more energy the biomass residues contain, and that can be converted, the greater the opportunities to offer high-value energy products such as bio-oil and green fuels.

However, not only energy prices determine the business case. Another important factor is that production takes place where it can efficiently market its energy products.

POSSIBLE SYMBIOSIS ECONOMY

Pyrolysis can be considered as a stop-end technology added as a final stage to other biomass treatment. The possibilities for co-location and synergy effects enhance the business case behind biochar. Read more in Chapter 7.

Pyrolysis can be located together with a biogas plant if residual fibres (digestate) constitute a relevant input to the biochar production. The logistics for biomass are already in place and the residual fibres only have marginal economic value. The input is more or less free of charge. Another advantage is that the pyrolysis process includes prior separation and dehydration of the digestate, which reduces the emissions of methane that would otherwise have occurred when the residual fibres were stored (avoided emissions), as well as improves the fertilising properties of the wet residue fraction when applied to fields[5].

Finally, the biogas plant can receive pyrolysis gas and surplus heat from the pyrolysis plant very easily if the two plants are located right next to each other. The pyrolysis gas can be added to the biogas plant for upgrading. Pyrolysis gas is generally not as clean as natural gas and cannot be sent into the natural gas grid without further processing.

However, the heat output from the pyrolysis gas will be relevant for industrial enterprises in the vicinity, for example. In turn, they may potentially have biomass residues that can be used to manufacture biochar.

Co-location, whereby different units and businesses exploit each other's residues or surplus energy circularly is well known from industrial and energy hubs such as GreenLab Skive. Pyrolysis is also an obvious element to incorporate in the upcoming energy hubs that were part of the 12 December 2023 political agreement.

NEED FOR REVENUES FROM CARBON STORAGE

Another vital element in the business case is that it offers some form of revenues or income from the carbon storage itself. This may come from selling carbon removal certificates, from a high willingness to pay from consumers, and from CCS subsidies for a limited period of time.

In addition to contributing to the pyrolysis process, there are costs associated with storing and spreading biochar, and documentation of the climate impact (via carbon removal certificates) also entails costs. For example, see SEGES Innovation (2023) for a more detailed description of the costs associated with obtaining carbon removal certification.

4.2. Why is biochar relevant for the individual farm?

Agriculture is an important part of the value chain behind carbon storage with biochar because the individual farm can both deliver relevant biomass residues and receive biochar for application on farm soil, with various benefits besides carbon storage. Agriculture is thus a crucial element at both ends of the value chain.

The following from the biochar and carbon storage process can have direct financial significance for the individual farm:

- Revenues from side streams such as straw residues, grass and livestock manure
- Good fertiliser (biochar) that is rich in phosphorus, has a low pH value, and could, to some extent, replace other fertilisers containing phosphorus, potassium and calcium
- Better return product for fertilising from biogas plants after separation and dehydration as a consequence of the pyrolysis process
- Share of profit from carbon storage

In contrast to other fertiliser products, biochar can be spread on fields the whole year round and is thus more flexible.
If a farm decides to supply its side streams to a pyrolysis plant, it may be an advantage for both parties to establish a long-term supplier contract that also reflects a green premium for the positive climate impact.

There are also other positive spin-off benefits for farms of applying biochar to soil and these relate to the soil-improvement properties of biochar, which may be difficult to valuate for the individual farm, but which are important at society level. As a general rule, Danish agricultural soil is already relatively fertile. With regards to the ability of biochar to increase yields from the soil, the best results are for sandy soils, and for crops with a high harvest value per hectare (Amonette et al., 2021).

See Chapter 5 for a more detailed description of the possible spin-off benefits of biochar for society.

The phosphorus cap entails that a maximum of 30 kg phosphorus can be spread per hectare per year. This corresponds to approximately the following quantities of biochar annually, depending on what biomass the biochar is made of:

- ½ t/ac (digestate)
- 0,8 t/ac (sewage sludge)
- 7-9 t/ac (straw residues)

Source: NIRAS (2023)

RISKS AND LIMITATIONS TO THE FARM

When using biochar as a fertiliser, the individual farm still has to comply with the annual phosphorous cap for agricultural soil. If the biochar is phosphorus-rich, for example because it is based on livestock manure, there will be limits on the amount of the biochar that can be spread on fields.

Because biochar "binds" different substances, it can inhibit the effect of pesticides and other agro-chemicals. Application must therefore be coordinated with this. To protect agricultural land from contamination from substances of concern, it is crucial that the content of biochar be tested, and that it complies with the relevant limit values in the same way as other products applied on agricultural land.

As there is currently no legal basis for using biochar made from agricultural residues on farmland in Denmark, threshold limit values must be introduced. As a precautionary measure, these could be based on the most restrictive existing limit values. See Chapter 6 on regulatory barriers.

5 Wet fraction with plant-available nutrients rather than residual fibers from biogas production, which are more difficult to convert in the field.

4.3. Business cases for biochar

The CIP Foundation has analysed the business case for biochar based on three different types of biomass and two different set-ups. In the simple version only pyrolysis gas, process heat and biochar are produced, whereas the extended set-up also produces bio-oil.

The calculations are based on producer information from AquaGreen (for sewage sludge) and from Stiesdal (for digestate and straw residues). See box 4.1 for a description of the processes and the energy balances, as well as Annex B for a description of the assumptions behind the business cases and the plants included in the business cases.

This approach has been selected to illustrate the significance of different input prices of biomasses. As well as the significance of using relatively dry biomasses compared with using biomasses that require prior and energy-intensive dehydration.

The approach also gives an idea about the energy balance in the overall process, showing how there is not "enough" energy left in all cases to be able to produce bio-oil as well. Bio-oil is more of a high-value product than pyrolysis gas, which is typically used for heating.

The purpose is to see whether total value-chain costs, including logistics, application and storage, can be covered by potential market-determined revenues.
Specifically, the analysis examines whether the costs of the six cases can be covered by the potential revenues from selling energy products, including sale of a climate credit at approx. EUR 100 or EUR 750.

Box 4.1: Three examples on biochar cases based on different biomasses

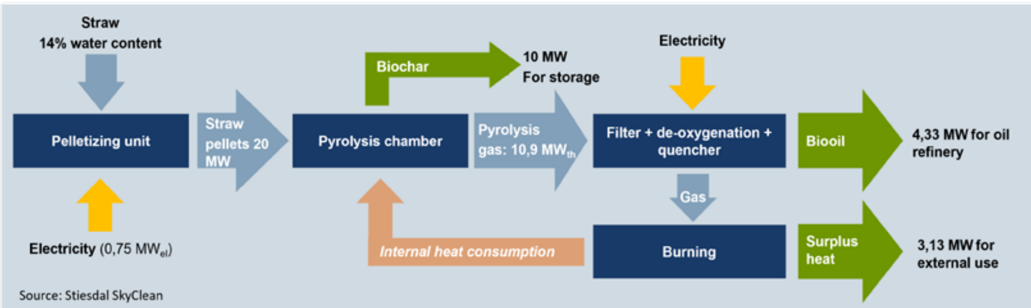
Case: Biochar from straw residues in extended set-up with bio-oil

Biomass

Process description

1. Residues do not need drying as the water content is only 14%
2. The straw is brought into a pelletizing machine, which pellets the straw.
3. The pelleted straw is brought into the pyrolysis chamber, where the energy in the straw is distributed between biochar and pyrolysis gas.
4. The pyrolysis gas can either be further processed into high-value products such as bio-oil, or set aside as surplus heat for, for example, district heating.

Heat balance



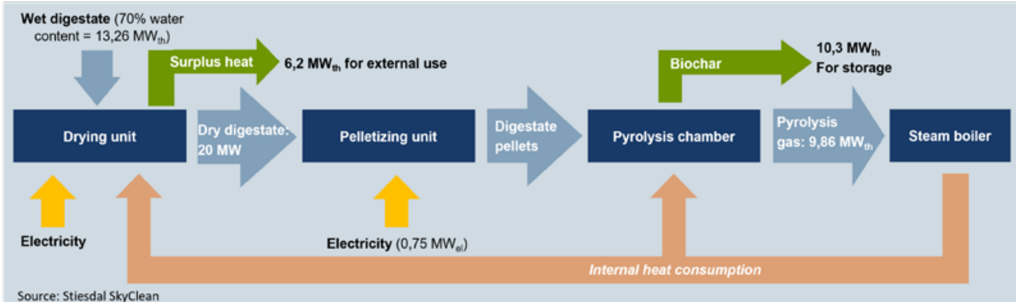
Case: Biochar from residual fibers from biogas in a simple set-up with pyrolysis gas and surplus heat

Biomass

Process description

1. Residual fibers from biogas (digestate) with 70% water content are put into a drying unit, which dries the digestate down to approx. 10% water content.
2. The dry digestate is brought into a pelletizing machine, which pellets the digestate.
3. The pelletized digestate is brought into the pyrolysis chamber, where the energy in the digestate is distributed between biochar and pyrolysis gas.
4. The pyrolysis gas is burned in a steam boiler to produce high-pressure steam.
5. The high-pressure steam is primarily used to dry the wet digestate using the drying unit. After the drying process, there is still excess low-temperature heat that can be used for external use.

Heat balance



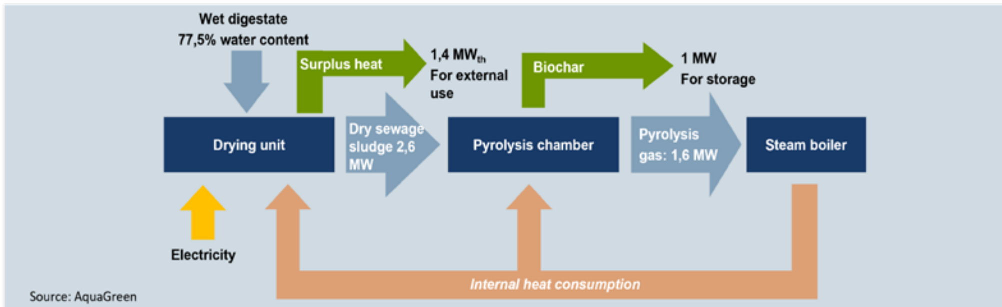
Case: Biochar from sewage sludge in a simple set-up

Biomass

Process description

1. Sewage sludge with a water content of 77.5% is brought into a drying unit which dries the sewage sludge.
2. The dried sewage sludge is brought into the pyrolysis chamber, where the energy in the sludge is distributed between biochar and pyrolysis gas.
3. The pyrolysis gas is burned in a steam boiler to produce heated steam.
4. The high-pressure steam is primarily used to dry the wet digestate using the drying unit. After the drying process, there is still excess low-temperature heat that can be used for external use.

Heat balance

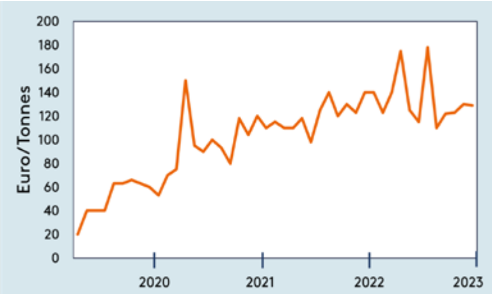


Different configurations will be relevant, depending on the biomass. In general, the use of straw residues or similar dry biomass residues will be the most relevant in relation to extended energy production (with bio-oil), while the use of wet biomass residues such as digestate and sewage sludge requires an energy-intensive dehydration process.

GREEN ENERGY AND CLIMATE CREDITS AS NECESSARY SOURCES OF INCOME

The most important revenues come from the sale of green energy from the pyrolysis

***Figure 4.1.** Rising prices for climate credits based on biochar*



Source: Carbon Removal Marketplace, part of CORC-CHAR index. Nasdaq.

process, i.e. pyrolysis gas/surplus heat, and in some set-ups bio-oil as well. Therefore, green energy, in particular, will pay for the costs of producing the biochar, which will then serve as carbon storage. In this context, the value can be set by the voluntary market for climate credits. The price of climate credits for biochar with long-term storage has increased over time, see figure 4.1.

The business cases are based on whether the carbon storage can be covered by a climate credit at a price of EUR 100 per tonne CO_2e. As climate credits for biochar were being sold at around EUR 130 per tonnes CO_2e the end of 2023, the assumption of a price of EUR 100 therefore seems plausible. But prices of climate credits with a 100-year storage effect are based on a fledgling market with a limited supply and with, so far, adequate demand.

There is extraordinarily high uncertainty regarding how the market for carbon removal certificates will develop in the future. Investors will have to valuate this uncertainty in the business case in which revenues from climate credits play a relatively large role.

See Chapter 3, #3, for a more detailed description of carbon removal certificates, and SEGES (2023) for an analysis of the market for climate credits.

CASE: BIOCHAR FROM RESIDUAL FIBRES FROM BIOGAS (DIGESTATE)

If the business case for producing biochar from digestate assumes the pyrolysis plant is located beside a biogas plant, then the input side has been dealt with in terms of logistics and acquisition price.

However, the biomass needs energy-intensive pre-processing to separate the fibre residues from the wet fraction and subsequently dry them. Part of the energy from the process must therefore be reserved for the pre-processing.

The case assumes an establishment price of DKK 150 mill. for a 20 MW pyrolysis plant for processing the residual fibres from biogas. See Annex B for an analysis of income and expenditure in the business case.

For biochar based on digestate, it is financially viable to produce the biogas in a simple set-up with pyrolysis gas (case 1), such that all the costs, including interest[6], can be covered with an additional income of up to EUR 100 from a climate credit. The case is robust, as the production cost per tonne of stored CO_2e is down to around DKK 430, which has to be covered through climate credits, for example.

In contrast, in case 2, with an extended set-up in which bio-oil is also made, production would not be financially viable, as there is not enough energy to allocate to bio-oil production. This is partly because the production process has already used part of the green energy for the dehydration process, and partly because the biomass has already released energy once before in the biogas process.

CASE: BIOCHAR FROM STRAW RESIDUES

Straw residues can be used directly in a pyrolysis process, but will entail costs to collect, transport and buy, because the biomass residues have competing purposes: incineration in heating plants, mixing in biogas plants and mulching on fields.

Although straw residues have a relatively high energy content, due to the purchase price of straw, the case is not profitable if the only green energy produced is pyrolysis gas/heat at relatively low prices as in case 3.

The straw case must be based on producing bio-oil too, which is a high-value product (case 4), even though this is also related to certain costs. The crucial element is the price that can be obtained for the bio-oil. With a bio-oil price of around DKK 600 per tonne, the costs needed to be covered with revenues from sale of climate credits is around DKK 680 per tonne CO_2e. As this is less than EUR 100 per tonne CO_2e, case 4 is also viable.

Assuming the bio-oil can be sold more or less unprocessed to a refinery (e.g. for further processing into advanced fuels), this may seem as a relatively high price compared with today's fossil alternatives.
In other words, bio-oil has a green premium. Without any major upgrading, bio-oil can be used in fuel blends for existing engines. Due to the new EU requirements for shipping fuels, for example, bio-oil can compete with expensive, sustainable e-fuels, and it does not require engine replacements.

See Annex B for an analysis of income and expenses.

CASE: BIOCHAR FROM SEWAGE SLUDGE

Today, treatment plants pay farms to spread sewage sludge on their fields. In other words, there are revenues in disposing of sewage sludge. Locating a pyrolysis plant next to a wastewater treatment plant means the business case starts to look promising.

However, the biomass requires significant prior dehydration, and this consumes a relatively large part of the energy balance.

Therefore, there is only likely to be enough energy to produce pyrolysis gas/heat (case 5), but not bio-oil as well (case 6).

Sewage sludge does not have a high carbon content after drying, so there is not much left in the biochar. Sales of climate credits are therefore not decisive for this business case.

However, there is a willingness to pay to dispose of sewage sludge and to have it remediated in the pyrolysis process. Wastewater treatment plants currently pay around DKK 300-400 per tonne of sludge to farms that apply it directly to fields to recycle nutrients, e.g. phosphorus from the biomass. So, in general, there is money in taking on this biomass. And as requirements to treat the sludge to remove substances of concern become

6 On an assumption of 8 percent return

stricter, the willingness to pay for pyrolysis will become greater.

The case involves three 2.6 MW pyrolysis plants at a cost of DKK 25 mill. each, with a total investment in pyrolysis and dehydration plants of approx. DKK 100 mill. to make cases comparable in terms of comprehensiveness.

Case 5 with sewage sludge is profitable with a willingness to pay at around DKK 570 per tonne of sewage sludge and sales of carbon removal certificates at around EUR 100 per tonne CO_2e. This case is more about environmental treatment of the sludge before any use of the biochar on fields (or elsewhere), than it is about carbon storage, which only accounts for around 10% of the revenues in this case. See Annex B for an analysis of income and expenditure in the business case.

The results of the business case are shown in table 4.2 with a brief explanation.

REMEDIATION OF PFAS IN SEWAGE SLUDGE

AquaGreen manufactures pyrolysis plants to treat sewage sludge, and the company has tested the ability of pyrolysis to degrade PFAS in the process[7]. Even though, sewage sludge generally contains a number of different types of PFAS, the result was that they could not be traced in the following tests[8].

There are many different types of PFAS, and if the process can degrade PFAS (in addition to the types tested for and without producing new hybrids), this could be a major technological and environmental step forward. Some Danish wastewater treatment plants are already linked with pyrolysis plants or are in the process of becoming linked (see Annex A, Danish production of biochar).

The business case for sewage sludge demonstrates the versatility of what can be achieved with pyrolysis. The more applications in which it is relevant, the greater the number of potential developers, and the greater the competition, innovation and technology.

BIOCHAR HAS SEVERAL RELEVANT CASES

The many types of relevant biomass and different set-ups for what energy products can be produced and sold, mean there are several relevant business cases.

The most obvious commercial case today is biochar production linked to biogas plants and based on digestate. This can be directly implemented with the technology and infrastructure already available.

In other words, where the biomass for biochar is already present (residual fibres form the biogas plant, typically based on livestock manure), and synergies in the input and the output can immediately be exploited. However, revenues are required for carbon storage in the biochar, for example through sales of carbon removal certificates.

Biochar made of straw residues from agriculture, for example hay residues and other crop residues, is relevant in a slightly more advanced set-up that also makes bio-oil to sell for more high-value purposes. According to requirements for the quality of the bio-oil, there may be a need for more development before the solution is ready for commercial use. However, there are huge perspectives if there is an entry to the market for green fuels.

In the long term, and in line with technological development and deployment of PtX, refining into advanced green fuels for aircraft, for example, may also be relevant.

Biochar based on sewage sludge is already possible technologically, but the process is energy-intensive, and this business model is primarily based on an ambition to remediate the biomass and on the willingness to pay for the positive environmental impact. Regulatory requirements for the treatment of sewage sludge could promote demand for biomass pyrolysis.

4.4. How much capacity should be built?

Development of a future market for pyrolysis and carbon storage via biochar requires market profitability in the project, as shown in this part, and that it is a good socio-economic investment, with positive effects. Furthermore, relevant framework conditions and regulation of the new technology must be established. Market development and good framework conditions go hand in hand.

Private players will not start developing significant capacity before they have clarification about a number of regulatory concerns (see Part 6) and have predictable and transparent framework conditions, while potential investors must also be able to secure long-term and stable supplies of both input (biomass residues) and output (storage via biochar).

Table 4.2. Can CO_2e storage with biochar be produced cheaper than DKK 750 per ton? Six different businesscases

	Preprocessing	Price of biomass	Simple value chain (pyrolysis gas, biochar and excess heat)	Extended value chain with biooil	Remarks
Digestate	Requires separation and drying	For free	1 ✓	2 ✗	The biomass is "free", and the process contains a good energy balance. Since the pyrolysis gas is used for drying and the excess heat for biogas upgrading, under current conditions there is no basis for expanding the value chain to also make bio-oil, as there is not enough energy left in relation to the costs. Will in that case require the use of another energy source (green electricity) for drying.
Straw	Ready to use	Cost	3 ✗	4 (✓)	The biomass requires payment as an input with increasing prices over time, as straw has other areas of application. But straw contains a lot of energy and carbon and does not require prior drying. The pyrolysis gas can thus form the basis for an extended value chain with bio-oil – the case depends on the selling price of bio-oil
Sewage sludge	Requires drying	Income	5 (✓)	6 ✗	The biomass involves a payment upon receipt ("gate fee"), but the process uses the pyrolysis gas for drying, which is why there is only a certain resale of excess heat. Requires a willingness to pay to get rid of the sewage sludge. Does not contain enough energy to also make bio-oil under current conditions.

Note: When the business case's positive result is in brackets, it means that the case is not robust against +/- 10 per cent. fluctuations in energy prices (income).
Source: The CIP Foundation based on companydata from respectively Stiesdal and AquaGreen

7 PFASs are so-called "eternal chemicals", which have typically been used to make something waterproof, wear-resistant, heat-resistant and/or grease- or dirt-repellent, cf. the Danish Environmental Protection Agency.
8 AquaGreen

How much capacity the market is interested in developing will depend on the conditions under which it has to take place, on the quantity of biomass residues available, and on local contexts affecting possibilities for co-location.

For example, if the political goal for agriculture of an annual 2 million tonnes of carbon storage via biochar is to be reached, depending on the type of plant and biomass, 70-90 plants of 20 MW will be required based on current technology available from Stiesdal. All else being equal, this will require investments in plant of around DKK 10-13 bn. at current prices.

Scaling could also take outset in the smaller installations, and it is possible to locate several plants on one site. See Part 7 on value chains, deployment and business models.

Over time, the technology will be improved, workflows and processes will be optimised, and various innovations will promote productivity opportunities. Over a period of years, capacity requirements can therefore be lower and expansion costs potentially less, as has also been seen when other technologies are scaled up and reach greater market maturity.

Internationally, it has been estimated that there may be a need for up to 380,000 biochar plants globally to help meet the objective of keeping temperature increases to well below 2 degrees Celsius by 2050 (Schmidt and Hageman, 2021). In the next phase of its biochar theme, the CIP Foundation will look more closely at the options in a global context.

The international potential is also significant for the more long-term perspective of investing in market development in Denmark. Valuable elements for future export potentials will include developing experience and competences, demonstrating stable supplies with documented effects, upscaling production, experience with market rewards for carbon storage, and other learning-effects.

4.5. How would a carbon tax affect the market for biochar?

The various business cases have been analysed assuming current regulations continue to apply for private players in the value chain. But what would happen if a carbon tax were introduced for agriculture? How would this affect the infant biochar market?

The Danish government wants to introduce a carbon tax on agricultural emissions with outset in a proposal from the expert group for green tax reform (Ekspertgruppen for Grøn Skattereform). In practice, it is likely there will be more political instruments in addition to a carbon tax, because there is an ambition to pursue several political targets at the same time. For example, lowering carbon emissions must not entail that production moves abroad and it must not impact employment.

Emissions from agriculture are not easy to calculate or measure, and it is therefore likely that initially plans will be for a relatively simple tax system based on existing documentation, for example farm accounts, which are easy to administer and have relatively few allowances and deductions.

There is little documentation at farm level of biochar as a climate measure through net carbon storage and this will have to be developed if biochar is to be seen as a tax instrument (deduction). And perhaps it is not such a good idea. Biochar should be used on fields with the greatest agricultural needs, and where the positive side-effects can best be utilised, and not where there is the greatest tax advantage. However, the carbon tax will still be significant for the biochar market.

From the farmers' perspective, a carbon tax will immediately make production-associated carbon emissions more expensive and will encourage investment in climate measures and conversion of production. This requires capital. In this context, biochar represents a path to new revenues from sales of side streams and/or storage of biochar. This applies regardless of whether a tax is introduced. However, a tax will intensify the need for new sources of revenues for farms and thus also the need for biochar production and carbon storage.

BIOCHAR REDUCES THE REDUCTION REQUIREMENT FOR AGRICULTURE

For agriculture as a whole, all the biochar stored on agricultural land will reduce the total reduction requirement for agriculture correspondingly. Even though climate credits are sold, the physical net storage in Denmark will still count in national and sector-based emission inventories. The collective gains in the form of lower net emissions from agriculture therefore entail a corresponding reduction in the need for a carbon tax or other requirements.

The introduction of a carbon tax in agriculture will, both individually and collectively, spur demand for biochar as a climate measure, and it will promote the market for biochar and carbon capture and storage.

How, and how much, depends on the specific design of a future carbon tax and on the use of other tools to reduce emissions.

For more information, read the CIP Foundation's background report on carbon taxes and the market for biochar (2024b) (in Danish) for a more detailed description.

What does society gain from it?

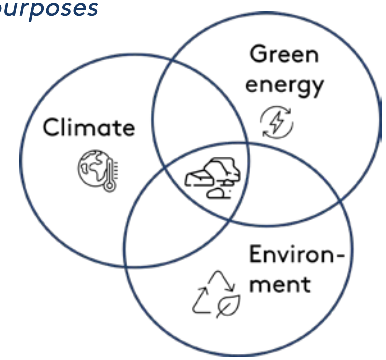
Chapter 5

Biochar is cost-effective compared to ther long-term CCS technologies and has significant climate effects beyond carbon storage and positive side-effects from its use.

5.1. Biochar provides positive climate impacts, green energy and environmental benefits

Production and use of biochar has a number of positive effects for society, ranging from positive climate impacts to the production of green energy and favourable environmental impacts.

Figure 5.1: *Biochar serves multiple purposes*



Source: The CIP Foundation's own graphic

CLIMATE IMPACTS WITH HUGE POTENTIAL
In 2018, the UN's climate panel IPCC recognised biochar as a Net Zero Emission Technology (NET) for the LULUCF sector, which includes agriculture. The UN considers biochar a climate technology with a global potential to remove 2.6 billion tonnes CO_2e annually[9] with substantial positive side-effects.

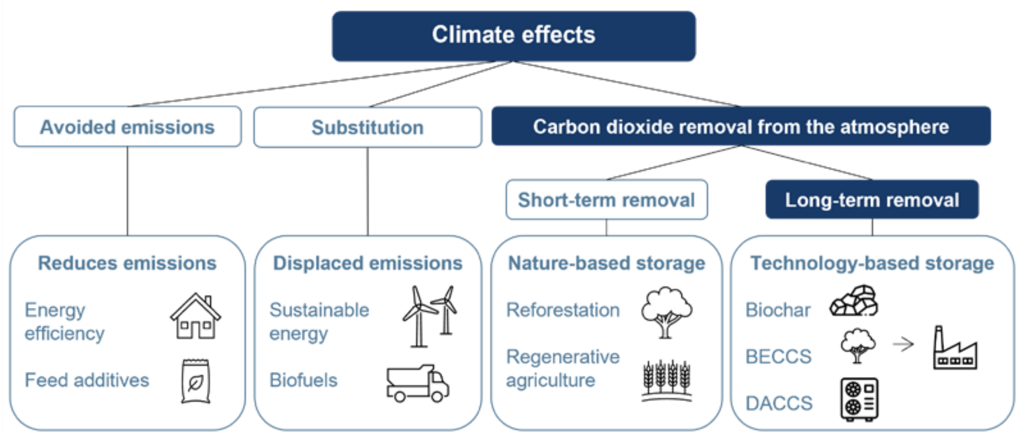
The Danish political agreement on green transition of the agricultural sector ("Landbrugsaftalen") from 2021 assessed a technical potential for biochar of 2 million tonnes CO_2e of carbon storage by 2030. This target may be revised with the government's upcoming pyrolysis strategy in 2024.

The work of the CIP Foundation in this report is to examine this potential and identify required actions to realise the potential.

CLIMATE EFFECTS BEYOND CARBON STORAGE
The primary climate motivation for biochar is the carbon-storage potentials. Pyrolytic treatment of biomass for biochar is a CCS (carbon capture and storage) technology. Other technologies with long-term carbon storage include direct air capture (DACCS) and carbon capture at point sources, for example from flue gas in a chimney, either fossil based or biogenic carbon (BECCS) with subsequent storage in geological formations.

As described in Chapter 3, #2, however, the process also leads to avoided emissions, in particular from processing wet biomass residues instead of recircalating them to farm lands directly leading to methane emissions.

Figure 5.2: *As a CCS-technology, biochar provides longterm and stable storage*



Source: The CIP Foundation's own graphic

Why store biogenic carbon today when the future needs it for PtX and green fuels?

When biomasses are pyrolysed, half of the carbon in the biomass ends up in the energy products (pyrolysis gas and bio-oil), while the other half ends up in the biochar. In other words, only 50% is stored and not available for future use.

The other half, however, is available for use through the green energy. And this 50% would not have been available, had biomasses not been collected for pyrolysis and biochar. So, making biochar stimulates demand for biomass residues, and more biogenic carbon is collected as a conssequence.

Pyrolysis gas (and bio-oil) can be processed into green fuels for aircraft and heavy transportation through PtX. This usually requires green hydrogen and carbon that may come from fossil sources. The pyrolysis process therefore provides more sustainable carbon alongside storing carbon from the atmosphere and recirculating important nutrients from the feed-stock.

The advantage of pyrolysis is that it simultaneously allows for carbon storage and provides new sources of carbon for PtX that are sustainable in the long run.

9 IPCC (2022): Climate Change 2022: Mitigation of Climate Change. IPCC Sixth Assessment Cycle (AR6), IPCC Working Group III.

Box 5.1: Environmental side effects of biochar on agricultural land

The most important societal benefits of biochar are the climate impacts from long-term carbon storage in the soil, from avoided emissions, and from the green energy that can replace fossil fuels. The private market contributes to paying for the carbon storage through climate credits, while a willingness to pay a green premium on green fuels is required to internalise that effect. The avoided emissions currently generate no market incomes.

However, biochar also has other side-effects linked to using the biochar on agricultural soil, for example. These side-effects not only impact the individual farm; they also have wider implications as externalities. Market willingness to take account of these side-effects is therefore somewhat unclear. Furthermore, results from the research literature on the size and impacct of potential side effects are not always clear. Therefore, valuation of side effects will entail uncertainty.

Examples of positive impacts of biochar on farm land:

- Soil improvement and potential to enhance cultivation properties of the soil
- Possble geographical redistribution of phosphorus and potash from biomass residues
- The pyrolysis process removes microplastics, medicine residues, pesticides and various heavy metals from the original biomass that would otherwise be used as fertiliser
- Improves the ability of the soil to retain the water for plants (greater drought resistance)
- Reduces leaching of nutrients (nitrogen) to wetlands
- Creates pores in the soil for biodiversity and increased microbial activity
- Binds substances of concern in the soil and reduces their biological accessibility

Examples of adverse impacts of biochar on farm land:

- Can increase salinity if added in very large quantities (beyond what is permitted, see the phosphorous cap)
- Risk of PAHs (tar substances) and other substances of concern in the biochar from the original biomass, if standard pyrolysis processes are not applied and the biochar is not tested on its content againts threshold values.

Although some international studies have found indications of adverse impacts, Danish test and trials with biochar on farm land so far have found no adverse effects. Other studies have observed ambiguous results and have given no clear conclusions as to the effects of biochar or have not examined the possible effects. For example, this applies to the risk of biochar leaching to the aquatic environment and the resulting potential impact on aquatic organisms. Finally, a better understanding is needed of the relationship between the amount of biochar applied and the resulting environmental impacts, etc. More research and testing are therefore needed to improve our understanding of the interaction between biochar and the environment in which it is applied.

Sources: Knowledge Synthesis on Biochar in Danish Agriculture, DCA report no. 208 from Aarhus University, 2022, and the CIP Foundation background memo on the potential environmental impacts of biochar (2024c) (in Danish) (2024c)

A positive climate impact also follows when the green energy from the pyrolysis process displaces fossil energy. These climate effects are also valuable to society and the climate.

As Denmark becomes more electrified and uses more green fuels, the displacement effect will be less significant in national inventories of climate emissions. However, in terms of the global climate, production of green energy from pyrolysis will continue to contribute to the displacement of fossil alternatives.

In addition to the climate impacts, a number of other side-effects are linked to biochar, some positive, and others potentially negative if precautions are not taken. See box 5.1. for example.

5.2. Possible environmental impacts of biochar on agricultural land

Many of the side-effects of biochar are related to biochar application on agricultural soils and the environmental impacts.

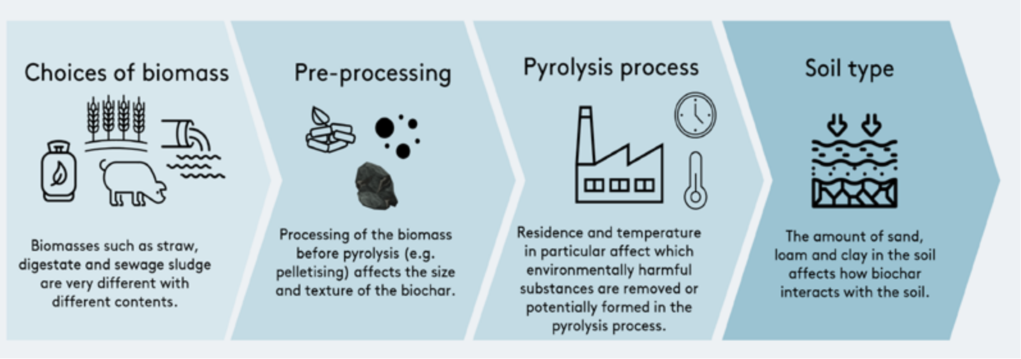
In a number of countries, in tropical environments in particular, the positive effect of biochar on soil properties and farm yield is well documented. The results are difficult to reproduce in temperate zones and on Danish agricultural soils because of the relatively high soil fertility from the outset.

Biochar has soil-enhancing properties because its structure helps to improve soil aeration and the soil's water-holding capacity. This can be beneficial for root development, and in sandy soils and soils exposed to long periods of drought due to climate change.

Furthermore, the pyrolysis process has been widely documented to remove substances of concern such as microplastics, medicine residues, pathogens, pesticide residues, etc. "Pyrolysis" derives from Greek and means separation by fire. Therefore, biomass can be said to be hygienised through the process of pyrolysis.

However, not all substances of concern in biomass can be removed through pyrolysis. Setting threshold values for the content of

Figure 5.3: The effects of biochar on agricultural land depend on several factors



Source: The CIP Foundation's own creation based on the description in the Knowledge Synthesis on biochar, Aarhus University, DCA report no. 208, 2022.

harmful substances in biochar is therefore necessary before using biochar, and standardised tests are required to check for compliance.

WHY ARE THE ENVIRONMENTAL IMPACTS SO DIFFICULT TO DETERMINE?
Although the volume of research literature on biochar is already extensive and is continuing to grow, it is difficult to extract unambiguous results of the effects of biochar.

Biochar is not "just biochar". Rather, it is an umbrella term for products from different types of biomass, processed differently and with differing structural properties, and which have gone through pyrolysis at different temperatures and with different residence times, see figure 5.3.

The environmental impacts also depend on the type of soil on which the biochar is applied. Soil is also not "just soil".

RESEARCH RESULTS NEED SYSTEMATISING
Results from research literature need a categorisation of impacts by type of biomass, processing and area of application. Reviews could compare different analyses and determine impacts for which there is high evidence, moderate evidence and low evidence, respectively. This would render research results more practice-oriented and provide a useful guide for the biochar application. This would, in turn, make it easier to aim for the positive impacts and take measures to avoid the potentially adverse impacts, depending on the specific context.

5.3. Is biochar a socio-economic justifiable climate measure?

The well-established climate results of biochar must be compared to its costs to society and potential side effects. In short, is biochar also a socio-economically justifiable climate measure? Or are there other, better and cheaper ways for society to displace carbon?

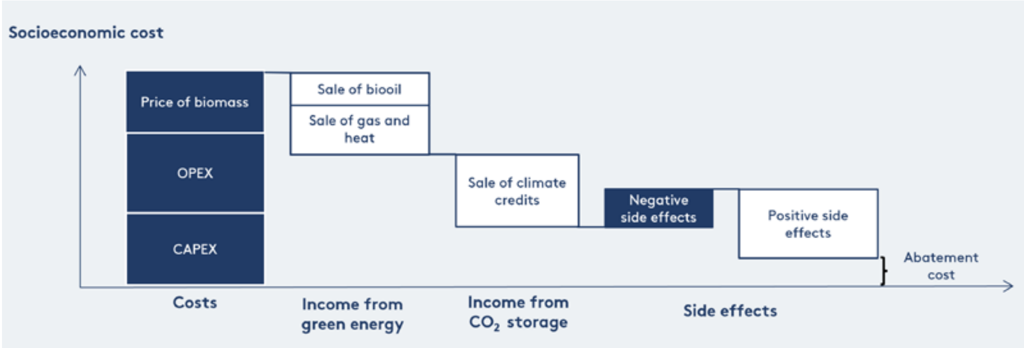
On behalf of the CIP Foundation, EA Energy Analyses (2024) has prepared an analysis of the socio-economic abatement cost of biochar made from straw and digestate (residual fibres from biogas production), respectively. The socio-economic abatement or shadow price is then compared to other CCS methods, BECCS and DACCS (see table 5.2 for characteristics of the varous methods).

The calculations assume a 20-year horizon for established plants based on a 20 MW pyrolysis plant, and a 84 MW BECCS plant (straw-fired heating plant).

The cost for society of displacing one tonne of CO_2 covers the following:

- Costs[10] (value chain costs for capital investments and reinvestments (CAPEX), operating costs, maintenance, climate certification and biochar storage and distribution costs (OPEX), as well as biomass procurement costs)
- Revenues (from sales of energy in the form bio-oil and pyrolysis gas/surplus heat)
- Sale of climate credits (future potential revenue stream is very uncertain)
- Side-effects (positive as well as adverse climate and environmental effects, typicyally not covered by market payments)

__Figure 5.4__: Illustration of the socio-economic shadow price for carbon storage with biochar



Source: The CIP Foundation's own illustration based on the method by EA Energy Analysis (2024)

See the illustration of elements in the methodology in figure 5.4. Note that this type of calculations are inherently associated with uncertainty.
Including side-effects and the possible willingness to pay for carbon storage with more traditional, long-term costs and revenues incurred and generated by private players will get you an indication of the socio-economic significance of the climate method. It will also produce the net cost of displacing one tonne of CO_2 and allow for comparison among climate measures.

The abatement cost or shadow price can also be compared with the EU-ETS price of carbon, which represents the cost of emitting one tonne of CO_2 within the ETS sectors in the EU. In general, it is significantly cheaper to emit a tonne of CO_2 that to abate a tonne of CO_2.

WHAT CLIMATE AND ENVIRONMENTAL SIDE-EFFECTS ARE INCLUDED?
As previously mentioned, the use of biochar is associated with a series of potential side-effects. However, not all of these have been unambiguously demonstrated, and their implications and possible costs or benefits are difficult to estimate. EA Energy Analyses has included the following side-effects in its analysis:

- Effective usage of nutrients in the feed-stock (nitrogen, phosphorous, potassium) when applied to farm land through biochar compared with the reference scenario[11]
- Calcification of the soil due to the pH value of the biochar, which reduces the need to apply calcium to the soil
- Potential particle pollution linked to the production of biochar
- Avoided emissions (nitrous oxide, methane and ammonia) when biomass is further processed and pyrolysed compared with the reference scenario

The analysis includes sensitivity analyses on various assumptions and the size of the effects.

The potential environmental benefit of biochar reducing nitrate leaching to wetlands is also analysed. Few methods are available to prevent this type of leaching, so this would potentially be a valuable effect. However,

10 Returns to private parties in the value chain are not included in socio-economic calculations.

11 Mulching of straw residues or application of residual fibers from biogas production on agricultural land.

the effect is also associated with much uncertainty as to its size and how much biochar is needed to achieve the effect, and further research and a better understanding of the effect is needed.

DISPLACEMENT EFFECTS HAVE NOT BEEN INCLUDED
The analysis from EA Energy Analyses does not include the possible climate benefit of green energy production (whether heat or fuels) that can potentially displace fossil alternatives. As fossil energy sources are set to be phased out of the Danish energy system in the long term, the potential for displacement in the Danish system is non-existent, and there will be no displacement effects to contribute to meeting Danish targets for climate neutrality, for example. However, the potential displacement effects are relevant to include in a global perspective, for example based on the green fuels that can be produced from some of the energy.

LARGE BENEFITS FROM AVOIDED METHANE EMISSIONS BY PROCESSING DIGESTATE
The analysis reveals positive side-effects for society from using biochar based on digestate, primarily because of the methane emissions avoided. Atmospheric methane is a very potent greenhouse gas. The effect of avoided emissions is primarily achieved by accelerating the process through drying, separating and compressing the digestate before pyrolysis. This separates them into a wet and a solid fraction. This approach leads to fewer methane emissions than merely storing the biogas fibres and then subsequently applying them to fields.

Pre-processing the digestate for pyrolysis is associated with costs, although these costs are offset by the total revenues in the business case. Biogas production alone,

***Table 5.1:** Socio-economic abatement costs for different methods of CCS*

	Biochar (digestate)	Biochar (straw)	BECCS (straw)	DACCS
Price per tonnes of stored CO_2e (DKK) at 100-year effect of the carbon storage				
Abatement costs excl. side effects and climate credits	-689	-248	-1.456	-1.500
Abatement costs incl. side effects and excl. climate credits	-455	-269	-1.531	-
Abatement costs incl. side effects and climate credits	43	229	-887	-

Note: Minus indicates cost and plus indicates gain. Private economic data for biocoal is based on a 20 MW plant, while BECCS is based on an extension to an existing 84 MW straw-fired cogeneration plant. Both based on a 20-year lifespan. DACCS is only assessed without climate credits and side effects. The data is subject to uncertainty. Source: Based on EA Energy Analysis (2024)

however, does not always offset the costs of this approach and the approach is therefore not common practice.

NEAR-NEUTRAL SIDE-EFFECTS FOR BIOCHAR BASED ON STRAW RESIDUES
The side-effects included for straw-based biochar are almost neutral, even when taking into account the loss of nutrients compared to the alternative of applying the straw residues directly on the fields.

BECCS HAS NEGATIVE SIDE-EFFECTS
For BECCS (burning straw in heating plants and capturing the CO_2 in the flue gas), the side-effects amount to a socio-economic cost. This is primarily because the nutrients in the biomass are not recirculated and exploited in the fields as they are in the reference scenario.

SALE OF GREEN ENERGY IS CRITICAL
The main scenario by EA Energy Analyses includes side-effects and the sale of climate credits.

For biochar based on biogas fibres, the green energy (pyrolysis gas) is assumed used to dry the biomass and to operate the pyrolysis process, while the remaining surplus heat (process heat) is sold to the nearby biogas plant for upgrading and possible use in the district heating network. For biochar based on straw residues, pyrolysis gas is assumed to be sold for district heating, and that the bio-oil produced can be blended with conventional fuel to make biofuels for ships, i.e. as a relatively high-value product. This is an important assumption.

For BECCS, it has been assumed that heat can be sold to the district heating grid and for production of green electricity. Without the sale of energy products, there would be no business case for carbon storage, regardless of the method applied.

THE FUTURE PRICES OF STRAW, BIO-OIL AND THE VALUE OF CLIMATE CREDITS ARE DETERMINING FOR THE BUSINESS CASE
The calculations are sensitive to assumptions on the development of straw prices, as straw constitutes an important source of biomass in two of the cases. Also, the assumption by EA Energy Analyses about the value of the sale of heat to the district heating network is based on a reference case with a straw boiler.

The future market price of bio-oil constitutes another uncertainty. The future market price of bio-oil depends on its use, and the analysis assumes that bio-oil will be used as a blending fuel in lieu of e-methanol. If bio-oil sold instead as crude oil for further processing, the price is likely to be lower.

Finally, the future revenues from climate credits are highly uncertain, as the market for climate credits is still under development, see Chapter 3, #5, for example. The climate credit market makes it possible to trade CCS as a service on market terms in line with trade in energy products. The market price of climate credits is not zero, but the long-term contribution from sales of climate credits is uncertain[12]. Therefore, the possible displacement costs or shadow prices of 1 tonne of CO_2 are shown both with and without climate credits.

THE SOCIO-ECONOMIC COST OF CCS
Table 5.1 shows the socio-economic abatement cost of storing one tonne of CO_2e using different CCS methods. This is the shadow price associated with displacing one tonne of CO_2e making it possible to compare different climate measures.

All climate measures shown in the table are associated with socio-economic costs from the outset, but the biochar methods are the

12 For biochar, it is assumed that a willingness to pay for CO_2 storage via the sale of climate credits of 40 percent of the quota price. For BECCS, a slightly higher willingness to pay is assumed due to security for storage beyong 1,000 years, corresponding to 50 percent of the quota price.

cheapest. This would also be the case if CCS based on fossil sources had been included, according to EA Energy Analyses.

Biochar as a CCS technology is therefore an attractive choice for society.

Including side-effects improves the price per tonne CO_2e sequestered by biochar made from digestate, which has relatively large positive side-effects. For biochar made from straw, the price is approximately unchanged, taking uncertainty into account, while the case worsens slightly for BECCS.

BIOCHAR IS A GOOD SOCIETAL INVESTMENT

If potential revenues from climate credits are also taken into account, the biochar solutions end up providing a small socio-economic gain, while BECCS is still associated with a socio-economic cost. This means that biochar has the potential to become a cost-neutral climate measure for the economy in the long run. This is rare.

BECCS, on the other hand, is associated with higher socio-economic costs per tonne CO_2e, primarily due to the relatively high market based costs.

Storing one tonne of CO_2e in biochar from digestate is generally associated with a socio-economic cost of approximately DKK 700. The price falls to DKK 450 per tonne CO_2e if the side-effects are taken into account. If the potential revenues from climate credits are also included, the climate measure ends up being cost-neutral for society. In fact, it is associated with a small gain of approximately DKK 40 per tonne of stored carbon.

CCS using biochar based on straw residues is generally associated with a relatively low cost for society of approximately DKK 250 per tonne CO_2e stored. Taking into account the potential side-effects does not change this significantly. However, if potential revenues from climate credits are also included, the picture changes and there is a small gain for society of approximately DKK 230 per tonne CO_2e stored.

Finally, the shadow price of CCS with BECCS is approximate DKK 1,450 per tonne of CO_2e. This price increases slightly if the possible side-effects are included. If potential revenues from climate credits are also included, the cost to society of BECCS amounts to just under DKK 900 per tonne of CO_2e stored.

OTHER ESTIMATES OF CCS

International studies of abatement costs (typically excluding side-effects and climate credits) also point to biochar as a cost-competitive technology compared to BECCS and DACCS, see table 5.2.

The Danish Ministry of Climate, Energy and Utilities (2022) has previously estimated the shadow price of biochar on the basis of technology subsidies from the Pyrolysis Pool to DKK 1,000-2,000 per tonne CO_2e, excluding side-effects, etc.

The Danish Council on Climate Change (2022) has estimated the long-term costs associated with biochar to be DKK 280-780 per tonne CO_2e.

***Table 5.2:** Different methods for long-term CO_2 storage – what are the advantages and disadvantages?*

What?	How?	Storage method	CO_2 source	Pros	Cons	Particular sector relevance	Socio-economic shadow price per tonnes of CO_2
Biochar	Biomass is pyrolysed to produce roughly even amounts of biochar and green energy, respectively.	The biochar is used as fertiliser on fields, as a component in materials, etc., which means the greater part of the carbon is stored stably for centuries.	Biogenic	• Produces green energy (pyrolysis gas, bio-oil and surplus heat) • Can manage a range of different types of biomass residues (flexible input) • Allows for co-location and synergies with other units • Is relatively easy to transport	• Biomass and biochar logistics infrastructure (may require collection and transportation from different locations) • Capacity threshold depends on the availability of biomass and the possibilities for selling the energy products	Agriculture as well as energy parks and other places with the possibility of co-location	Low-medium IPCC (2022): 10-345 USD per tonne (TRL 6-7) EA Energy analysis: 20-100 USD per ton (2040 prices)
BECCS	Biomass is burned at power plants or at large industrial facilities with point-source carbon capture	The captured carbon is compressed and stored permanently underground (geological storage)	Biogenic	• Produces green energy (heat, which is then converted to electricity) • Large-scale CCS from large point sources • Can capture the major part of the carbon from biomass in point source emissions	• Biomass logistics infrastructure • Requires infrastructure for liquid CO2 for underground storage • Requires infrastructure for liquid CO2 for underground storage	Energy sector and at larger industrial plants	Low-Medium IPCC (2022): 15-400 USD per tonne (TRL 5-6) EA Energy analysis: 100-200 USD per tonne (2040 prices)
DACCS	Extraction of CO_2 from the atmosphere through chemical processes (CO_2 comprises 0.04% of the atmosphere)	The captured carbon is compressed and stored permanently underground (geological storage)	Fossil/ biogenic	• Does not require large areas of land (requires no land for growing biomass) • Is flexible in terms of siting and size	• Is still an emergent technology • Relatively expensive • Energy-intensive (capturing only few CO2 molecules requires filtering large amounts of air) • Requires infrastructure for liquid CO2 for underground storage	Independent location	Medium IPCC: 100-300 USD per tonne (TRL 6) EA Energy analysis: 200-400 USD per tonne (2040 prices)

Source: : IEA (https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/direct-air-capture), IEA (https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/bioenergy-with-carbon-capture-and-storage) , IPCC (2022b), EA Energy Analyses (2024)

The estimates by EA Energy Analyses are significantly lower when climate impacts and possible side-effects are included, but they are on a par with estimates by the Danish Council on Climate Change when climate impacts and side-effects are excluded.

CCS IS RELEVANT COMPARED WITH OTHER CLIMATE MEASURES

In general, the cost for society of displacing one tonne of CO_2e is approximately DKK 1,500 across technologies (e.g. see Danish Council on Climate Change 2023, IEA 2022, IPCC 2022 and EEA 2021).

In comparison, under the EU ETS scheme, emitting one tonne of carbon today costs just under DKK 700. A price that is expected to increase to DKK 1,100 per tonne by 2035 (Danish Energy Agency, 2023) On the basis of this, the Danish Energy Agency has estimated the marginal emission reduction cost of climate adaptation to be DKK 738 per tonne CO_2e in 2030, see the Agency's report on assumptions for socio-economic analyses (2022).

Compared to other estimates, the work of EA Energy Analyses therefore supports a conclusion that biochar as carbon storage and climate measure comes at a competitive price.

BIOCHAR MAKES GOOD SOCIO-ECONOMIC SENSE

The structural benefits of this technology come from its effective exploitation of biomass residues, which leads to positive climate impacts, green energy and potentially also environmental benefits.

The risks associated with using biochar are linked in particular to the risk of unknown future effects of long-term use. Market deployment should therefore be supported by a research programme and knowledge build-up on the use of biochar, as well as through long-term trials to supplement existing knowledge informing today's use of tolerance thresholds for fertiliser products, and to guide the application of biochar.

5.4. Other socio-economic effects of biochar

Biochar based on biomass residues is typically produced in relatively rural areas close to where the biomass is sourced. Biochar production provides a new type of energy and industrial production, with associated derived activities at suppliers and buyers. These new activities and associated jobs are likely to be placed in rural areas.

See figure 5.5. for a geographical distribution of the largest biomass residues resources in Denmark by carbon content. These are typically concentrated in areas with relatively low economic activity, and the establishment of a new industry based on biomass will affect local possibilities for economic growth and job creation.

LOCAL JOB CREATION

In terms of job creation, the establishment of a pyrolysis industry in Denmark with production and storage corresponding to the political target of 2 million tonnes CO_2e, will lead to the creation of new local jobs during the establishment phase of up to 70-90 plants of 20 MW, that is needed to achieve the political goal.

New jobs will also be created for the subsequent operation and maintenance phase, as well as in the ancillary industry for biomass supply and biochar procurement.

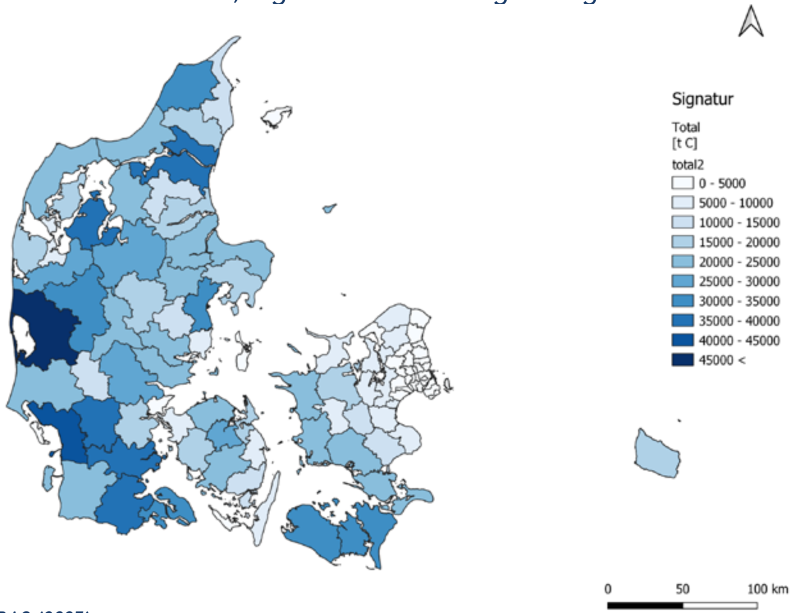
In addition to jobs and derived activities, biochar production will also generate ancillary revenues from side streams for those who supply the biomass and store the biochar.

BUSINESS STRUCTURE SYNERGIES

Danish pyrolysis capacity is likely to be scaled up throughout the country, but always in some proximity to where the biomass resources are located and with varying plant capacities, see Chapter 7.

Like the establishment of the biogas sector, a new pyrolysis industry will affect the local business structure. New plants could benefit from being located close to an existing biomass logistics infrastructure, for example linked to wastewater treatment plants, biogas plants and other businesses with relevant biomass residues, as well as close to existing energy buyers, see Chapter 7. In other words, siting of plants should consider possible synergy effects from co-location. Establishment of a new industry with pyrolysis plants is therefore expected to promote business developments, with the establishment of local energy hubs and business clusters that buy and sell waste products and surplus energy from each other, and with pyrolysis plants as the final link in the value chain.

***Figure 5.5**: Location of residual biomass in Denmark according to carbon content in straw residues, digestate and sewage sludge*



Source: NIRAS (2023)

What does existing regulation say about biochar?

Chapter 6

Market deployment and use of biochar in Denmark is made difficult by inconsistent regulation and a lack of clarification as to what biochar and pyrolysis are legally. Several processes could be simplified, but the precautionary principle should be observed in relation to the contents of contaminants, etc. in biochar.

6.1. International approach to biochar

Production of biochar through pyrolysis is nothing new. However, in a regulatory context, biochar is a relatively new phenomenon, also in Denmark.

THE UN CONSIDERS BIOCHAR A "REMOVAL" TECHNOLOGY

The UN's climate body, the IPCC, has recognized biochar as a Negative Emission Technology (NET) since 2018 and as one of the technologies that must deployed if we are to achieve the Paris Agreement's target of a maximum temperature rise of no more than 1.5 degrees Celsius. The potential is estimated at 2.5 billion tonnes of global carbon storage (IPCC 2022).

THE EU ACKNOWLEDGES BIOCHAR AS A FERTILISER

The EU also has a definition of biochar. The revised Fertilizer Regulation (in Danish "Gødningsforordning") was introduced in summer 2022, and it included biochar for the first time as a recognized fertilizer product in agriculture, provided it is based on agricultural by-products in the form of plant residues and livestock manure. The EU also presented rules for how to obtain CE marking of biochar, so that it can be placed on the market and sold across national borders within the EU.

EU **regulations** (in Danish "forordning") are immediately applicable in EU Member States and therefore become part of the legal system of Member States without prior national implementation. Regulations are binding and thus introduce rights and obligations on an equal footing with national legislation.

Source: The Danish Parliament's EU Information

CE marking of biochar as a fertiliser product requires approval by a notified body, and no such body currently exists in Denmark[13]. CE marking of a biochar product is an indication that the product meets a number of requirements regarding its content, but CE marking does not equate to authorisation to use the biochar on agricultural land in individual Member States, because national legislation may have certain environmental regulations that prevent this.

ORGANIC FARMS ARE ALLOWED TO USE BIOCHAR OF PLANT ORIGIN

When the EU's Organic Regulation (in Danish "Økologiforordning") was revised in 2021, the regulation's list of products and substances "authorised" for use in organic production was extended with naturally occurring products such as biochar, mollusc waste, eggshells, etc. However, this only applies to biochar produced from plant materials and under certain circumstances. See the CIP Foundation's background report on regulation (2024) for a more detailed description.

EU CARBON REMOVAL CERTIFICATION FRAMEWORK

The EU has also initiated development of a certification framework (MRV, monitoring, reporting and verification)[14] to certify carbon storage (i.e. carbon removals) and to promote transparency and more uniform market opportunities for monetization of carbon storage across a range of CCS technologies, including biochar. Work on this is expected to be completed in 2028.

As part of work on a standardised framework for certifying and verifying carbon removals, the EU will also consider the duration of carbon storage for different methods and technologies, from cultivation methods with regenerative farming practices to afforestation, as well as the more technical methods of storing carbon such as via biochar, BECCS and DACCS.

Tripartite negotiations (trilogues) are currently taking place between the Parliament, the Council and the Commission, and these are expected to end in early 2024. The negotiations will not necessarily result in a final decision on the status of biochar. Biochar could potentially be categorised as a medium-term storage method, in contrast to underground geological storage, for example, which will likely be categorised as a permanent storage method. Work will subsequently continue in expert committees. The categorisation of methods according to storage duration will help inform the market for climate credits in relation to the valuation of carbon removal certificates. The longer the storage, the higher the price. But the price will also depend on the specific project, as well as on documentation and credibility.

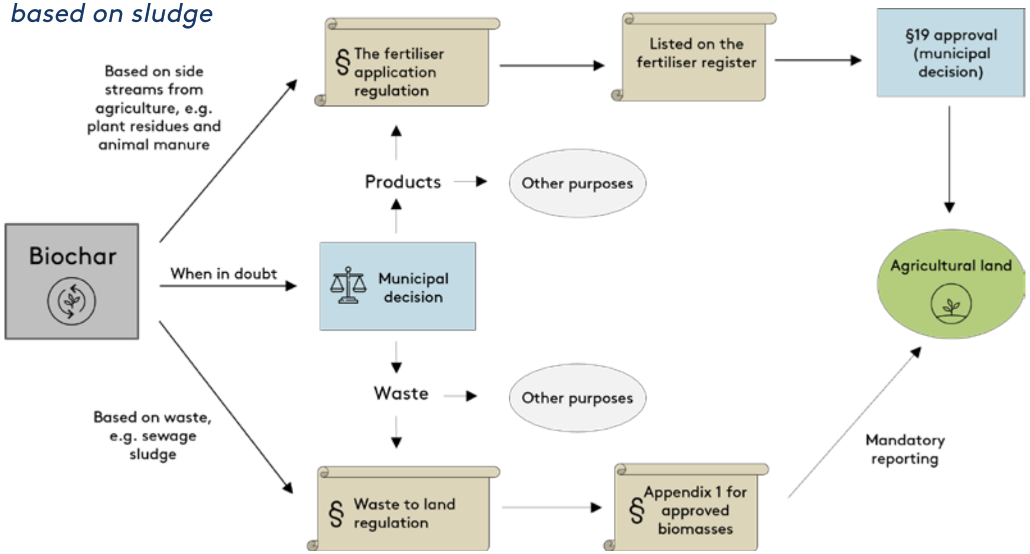
For example, see Chapter 3, #4, for details about the duration of carbon storage by biochar and #5 for facts about carbon removal certificates.

6.2. Biochar in Danish regulation

Biochar has so far only been indirectly regulated in Danish legislation, typically through regulations on the use of biomass. In summer 2023, biochar was introduced in Danish regulation for the first time, namely in the new Fertiliser Use Order ("Gødningsanvendelsesbekendtgørelse")and in the new Fertiliser Use 2023/2024 Order ("Gødskningsbekendtgørelse")from the Danish Agricultural Agency.

13 A notified body is, cf. the Danish Agency for Agricultural Medicines, an independent third party (e.g. a company) who, for a fee, can assess and judge that fertilizer products meet the applicable requirements of the EU's fertilizer regulation. Conformity assessment bodies must be able to offer laboratory analyzes of fertilizer products or certification of fertilizer products, etc. There are around 14 approved conformity assessment bodies in the EU, including 3 in the Netherlands, cf. Update on Fertilising Product Regulation (EU) no. 2019/1009 (FPR) (staphyt.com). You can apply for CE approval in other countries. 14 EU Horizon project C-Sink

Figur 6.1: Different requirements for biochar on agricultural land – easiest if based on sludge



Source: The CIP Foundation's own graphic

The two orders include rules on how to use biochar in agriculture; that is, the application methods allowed for biochar; when biochar may be applied; and how to document the use of biochar in the farm's fertiliser accounts.

IT IS GENERALLY NOT PERMITTED TO USE BIOCHAR IN AGRICULTURE IN DENMARK

The new orders do not provide a legal basis to use biochar, and it is generally not permitted to use biochar if it is made from agricultural residuals (side streams) such as plant residues and livestock manure. This applies even if the biochar has been approved for sale on the market as a fertiliser product and has been included in the Fertiliser register (in Danish "Gødningsfortegnelsen"), for example.

Application of biochar based on agricultural residues on agricultural soils requires separate approval (a Section 19 approval, in Danish "§19 godkendelse") by the municipality.

The Section 19 approval under the Danish Environmental Protection Act (in Danish "Miljøbeskyttelsesloven") is a broad provision by which local authorities can allow for substances, products or materials that could pose a risk of contamination when applied to soils. For biochar from agricultural residues there is no direct regulation and hence the need for the Section 19 approval.

Figure 6.1 shows the regulatory pathways for biochar application on soils in Denmark depending on the type of biomass used. For biochar based on agricultural residues such as plant residues and livestock manure, application on agricultural soils requires a special Section 19 approval, which is a temporary approval issued by the relevant municipality authorising the owner of the approval to apply a specific quantity of biochar made from a specific type of biomass on specified plots of land.

Box 6.1: Section 19 approval ("Risk of contaminated soil")

Before a plant or business can reuse pure or contaminated soil or use products (not regulated by other legislation) that will come into contact with soil and groundwater, they must obtain approval under Section 19 of the Danish Environmental Protection Act.

Section 19 of the Danish Environmental Protection Act states that contaminated soil or other products that can negatively affect groundwater, soil and the subsoil must not be used without prior approval.

Approval is granted by the municipal council. The expected processing time for an application for approval is 8-12 weeks. The process includes a consultation period of up to four weeks, during which the Patient Safety Authority will be consulted, among others.

Approvals granted pursuant to Section 19 may be changed or withdrawn at any time, and without compensation, on grounds of danger of contamination or pollution of water supplies, implementation of wastewater drainage, or other concerns to protect the environment. The approval is time-limited. In general, the approval period is determined by the local authority and may vary.

Section 19 approvals impede the establishment of a real market for biochar because they:

- Are temporary
- Only apply to specific plots of land
- Can be withdrawn
- Require time-consuming administrative work by the municipality as well as by the applicant
- Entail a risk of variation in case processing at local level
- Tend to link biochar with soil contamination, which could be perceived negatively by cooperation partners of the individual farm, such as banks, mortgage-credit institutions as well as food producers and suppliers of feed, seeds and fertilisers.

Sources: Danish Environmental Protection Act, Section 19 (danskelove.dk)

Section 19 approvals can be granted to authorise the application of substances, products or materials not regulated by other legislation. See the fact box 6.1 for more details about Section 19 approvals and the importance of this provision for the large-scale deployment of biochar as a climate measure.

IT IS PERMITTED TO USE BIOCHAR FROM SEWAGE SLUDGE

The Waste-to-soil Order (in Danish "Affald-til-jord-bekendtgørelsen") includes a legal basis for applying biochar sourced from biomass waste products such as sewage sludge on agricultural soils, provided the biomass waste product is included in the list in Appendix 1 of the order. This is because the pyrolysis process is considered a way of processing/treating the biomass.

It seems **paradoxical** that Danish legislation allows for the use of biochar on agricultural soils if the biochar is based on waste products that could contain a number of hazardous substances, whereas use of biochar based on purer types of biomass, such as straw or grass residues, requires special environmental approval.

If there is doubt about how to categorise the biomass used to produce biochar, the municipality will have the final say in deciding what legislation applies. In conclusion, understanding regulation in the area, including Sector 19 approvals, requires extensive knowledge at local authority level about biochar and the possible implications of using various types of biomass.

INCONSISTENT REGULATION

It is probably for historical reasons that the potential use of biochar in agriculture differs so much depending on the type of feed-stock, and why so much is left to local decisions. Farmers have so far been granted approval to use sewage sludge as a fertiliser product pursuant to the Waste-to-soil Order ("Affald-til-jord bekendtgørelsen"), because there has been a sentiment in Denmark towards promoting nutrient recycling in agriculture. But other agricultural residues have relevant nutrients to recycle too.

BIOCHAR REGULATION WITH THRESHOLD VALUES SHOULD BE CONSIDERED

Instead of indirect regulation of biochar through the various feed-stocks and residues regulations it is import to start looking at biochar as a fertilizer product with the potential for recycling phosphorous, for example. In other words, a legal basis for applying biochar to agricultural soils should be considered. As biochar can be produced from a number of different types of biomass residues, legal authority to use biochar should be independent of the type of biomass used, as otherwise many different legislations may apply. And some biomass residues (mixed types, in particular) are not subject to regulation today.

The phosphorous cap (in Danish "fosforloftet") only allows for a maximum of 30 kg phosphorous per hectare per year on average across the farm's soils. The content of phosphorous in biochar differs depending on the biomass used.

Phosphorous biomass types (which stem from livestock manure or sludge, for example) contain more phosphorous than plant residues such as straw and grass, and the concentration of phosphorous increases after drying and pyrolysis.

The Fertiliser Order considers the release of phosphorous from biochar to be immediate, meaning that it has an effect in the first year of application. However, if the plant-available phosphorous release happens slightly slower and over several years, the rules should perhaps be changed to prevent inadequate phosphorous application the first year and possible accumulation of phosphorous after several years of application.

Sources: Knowledge Synthesis on Biochar in Danish Agriculture, DCA report no. 208 from Aarhus University, 2022, The Danish Agricultural Agency and the CIP Foundation background report on regulation

The new biochar regulation must include threshold values for the content of potential contaminants. Compliance with these threshold values could be checked in conjunction with the testing of biochar batches already being carried out by producers. A precautionary approach should be applied, so that, regardless of the biomass used, the outset is the most restrictive existing threshold values for fertiliser products. So far, no negative impacts have been observed from the application of biochar to Danish agricultural soils. However, there is still a need for trials and more knowledge about the long-term effects. As new knowledge and insights are formed, the regulations can be tightened or relaxed accordingly. This type of legislative framework, i.e. one that can be adjusted over time, is well known from other new markets with only limited or short-term experience on the use of the new products. The EU has taken the same approach in regulation of the new Power-to-X markets.

EXAMPLE: Biochar in Danish building materials

Because of its properties to improve other materials, biochar can be used to improve building materials and create carbon sinks in the built environment.

Biochar can replace scarce and virgin resources such as sand, gravel and fossil activated charcoal and be used as an admixture in concrete, asphalt, stormwater systems and building blocks.

Biochar is also a heat and humidity regulator, and Saint-Gobain Danmark, for example, is developing a patented biochar component for floor insulation between storeys and on ground floors in particular, because the high stability of biochar makes it well-suited for contact with the soil.

Recent years have seen annual average new construction of around 6 million m2 of residential and commercial buildings in Denmark according to Statistics Denmark.

An example: If each m^2 floor area includes 10 cm^3 biochar in 75% of the average new floor area, the required annual amount of biochar needed would amount to 180,000 tonnes, corresponding to storage of 500,000 tonnes of carbon. This corresponds to the annual production capacity of around 18, 20 MW pyrolysis plants, and these will also be able to produce heat, gas and oil for other industries than the building and construction sector.

Source: Saint Gobain Denmark, Stiesdal SkyClean and the CIP Foundation

INSPIRATION FROM EXISTING THRESHOLD VALUES

There are several existing threshold values of relevance to biochar. For example, from the Waste-to-Soil Order (in Danish "Affald-til-jord-bekendtgørelsen"), the EU's CE-marking of biochar, as well as from other fertiliser products and carbon removal certificates for biochar, which also set requirements for biochar content in order to prevent possible negative environmental and sustainability effects.

Finland and Germany, for example, base their threshold values for biochar used as a fertiliser product on the EU's Fertilising Products Regulation. Finnish legislation also allows for sewage sludge and industrial waste to be used for biochar under certain conditions, including requirements for the pyrolysis process and contents in the biochar[15].

HOW MUCH BIOCHAR CAN BE APPLIED TO FIELDS?

In addition to a Section 19 approval or legal authority under the Waste-to-Soil Order, farmers are also subject to indirect regulation of the amounts of biochar they can apply to their fields. This comes from the so-called phosphorous cap (in Danish "fosforloftet"), which regulates the application of fertiliser to soil at the individual farm. And hence, how much biochar to apply depending on the content of phosphorous in the biochar.

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GEOGRAPHICAL REDISTRIBUTION OF PHOSPHORUS
As certain types of biochar contain relatively high concentrations of phosphorous, and as biochar is relatively easy to transport, it is possible to redistribute the phosphorous reserve from pfosphorous rich areas of the country to areas in need of more phosphorous (i.e. from eastern to western Denmark).

Phosphorous, which is a vital product in agriculture and a necessary nutrient for all living organisms, is a scarce resource globally[16]. The same applies for potassium, which is also retained in the transition from biomass to biochar. Soil can be improved by adding phosphorous, and the general sentiment is to recirculate this resource as much as possible.

USE OF BIOCHAR IN BUILDING AND CONSTRUCTION
Biochar has other areas of application than using it to improve soil conditions in agriculture. For example, see Chapter 3, #1. In the building and construction sector, for example, biochar in building materials can lower the climate footprint of the sector and make building materials more sustainable.

There may be building regulations to follow depending on what the building material is used for. For example, building and construction in Denmark is subject to legislative requirements for exterior building materials, roofing, façades and materials used for load-bearing constructions, floor constructions between storeys, etc. According to the Videncentret Bolius knowledge centre, these requirements concern such things as material strength, fire resistance and the health impacts of materials. Furthermore, building materials covered by the building regulations are subject to approval by the Danish Transport, Construction and Housing Authority.

The requirements for materials are supported by the Danish Standards Association (DS), which publishes standards, etc. regarding building materials in close alignment with the rules in relevant building regulations. Furthermore, standards from DS specify the building regulation rules on certain areas such as building design/construction and installations, etc. see Videncentret Bolius.

If biochar is used in other sectors than the agriculture sector, the resulting carbon removals cannot be included in Danish national emission inventories, because, according to the IPCC's rules on emissions inventories, there are no categories other than LULUCF in which to include biochar[17]. Increased use of biochar could help make national experts aware of these classification rules.

6.3. Relevant locations for pyrolysis plants

A pyrolysis plant is generally considered an industrial plant that also produces green energy. Pursuant to the Planning Act, industrial plants must be sited in industrial areas (urban zones designated for industry), and these are typically located on the outskirts of cities and towns, not in the rural zone.

***Box 6.2**: Approval processes for the establishment of pyrolysis plants*

As with the establishment of other industrial and energy plants, establishing a pyrolysis plant requires obtaining a series of approvals. With regard to options for siting a pyrolysis plant under the Planning Act, see section 6.3. Furthermore, options for using the output, i.e. the biochar, are described in section 6.2, including a description of the so-called Section 19 approvals that will need to be applied for regularly.

Other potential approvals also need to be obtained during the planning process in relation to design decisions about the technical plant. For example, the pyrolysis plant must be assessed with regard to its environmental classification and, depending on the relevant environmental class, there will be different requirements for carrying out an EIA. The requirements for an EIA depend on whether the installation in question is to be considered an Annex-1 or an Annex-2 installation according to the Ministry of Environment of Denmark's Environmental Approval Order. Annex-1 installations only need to comply with a simplified approval system with reduced disclosure requirements, see the Danish Environmental Protection Agency.

So far, no guidelines or similar exist which describe when a pyrolysis plant can be considered a technical installation. It is up to the individual municipality to decide this based on such details as the size of pyrolysis plant, the biomass input, and the main output from the plant (pyrolysis gas, bio-oil or biochar). Clear standard examples from central level on how to determine the environmental classification of pyrolysis plants could reduce the time needed to plan and establish pyrolysis plants. Furthermore, the Danish government should promote harmonisation of this across the EU through the IE Directive.

The approval processes affect the total time required to establish biochar production and, thus, the time it will take before climate impacts can be realised.

Source: See the CIP Foundation background report on regulation (2024a), for example.

Options for promoting biochar capacity deployment

Promote investment decisions through greater certainty about revenues and costs

- Establish a legal basis for the use of biochar from agricultural residues, so that actors can enter into agreements with buyers before establishing the plant
- Establish a temporary CCS subsidy scheme to carry some of the costs of carbon storage and eliminate some of the uncertainty about revenues from climate credits as the market is developing
- Establish threshold values for the contents of harmful substances, etc. in biochar (to be incorporated into standard testing) to allow for greater certainty about the actual application of the biochar produced

Shorten the time frame for approval

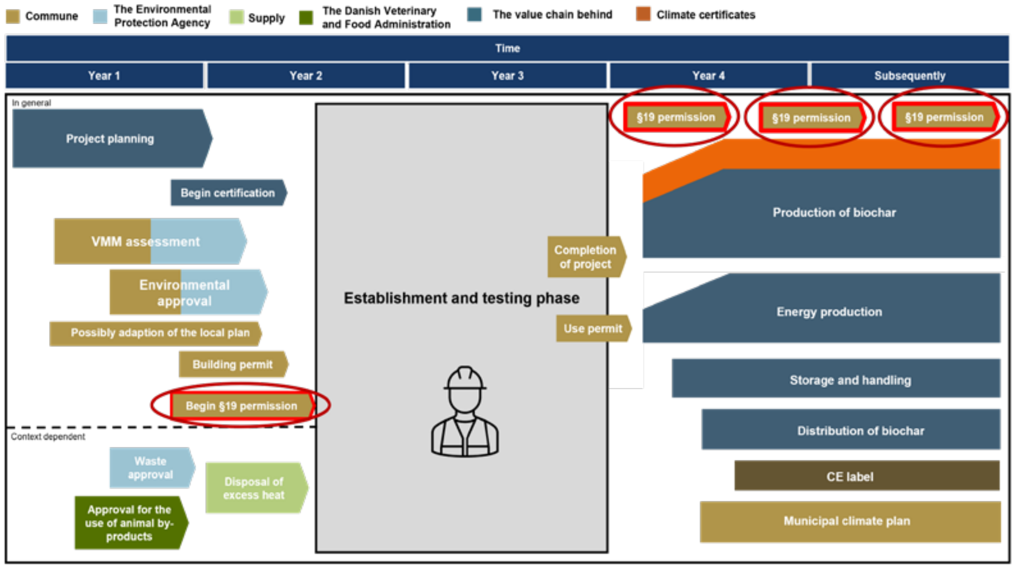
- Make a decision on the environmental classification of various types of pyrolysis plants (Annex-1 or Annex-2 installations) and, thus, the required environmental approval process, and provide standard examples to guide municipal case processing

Exploit synergies by siting pyrolysis plants near existing biogas plants and energy hubs

- Equate pyrolysis plants with biogas plants in the Planning Act to allow pyrolysis plants to be located in rural zones without having to change the local development plan (allow for co-location)
- Include the possibility to place pyrolysis plants in areas which, in consultation with the municipalities, are being considered designated for new energy hubs and new biogas plant

16 Knowledge Synthesis about phosphorus, Poulsen et al (2019), Aarhus University, DCE – National Center for Environment & Energy.
17 Nielsen, O.K. (2022).

***Figure 6.2:** Establishment of biochar production and examples of processes*



Source: The CIP Foundation's own graphic

However, the most obvious place to site a pyrolysis plant for biochar based on side streams from agriculture will often be near to where the biomass is sourced; that is, in the rural zone. Siting in rural zones is a possibility but requires approval by justifying the need to locate the plant in the open countryside and then adjusting the relevant local development plan. Any adjustments to the local development plan must not conflict with the more general municipal development plan, and relevant local stakeholders must be consulted on the proposed changes.

Experience from the establishment of biogas plants could serve as inspiration. Biogas plants were also once subject to siting restrictions, but these plants have since been included in the list of exemptions from the rule of siting industrial plants in industrial areas. The same should be considered for pyrolysis plants. For example, it would be obvious to locate pyrolysis plants in conjunction with biogas plants if the biochar were produced from residual fibres from biogas production. See also figure 6.2 for a detailed illustration of approval processes for the establishment of pyrolysis plants.

6.4. Financial support for biochar

So far, biochar and pyrolysis have been subsidised through various research and testing and demonstration funding schemes. For example, the Danish Agricultural Agency has subsidised a number of biochar projects through the Green Development and Demonstration Programme (GUDP), with projects on biochar produced from everything from pig slurry to poultry manure, grass pulp and sewage sludge. Other research projects concern the development of the biochar value chain and are supported by Innovation Fund Denmark's INNO-CCUS Partnership, for example. The Partnership supports projects within biogenic carbon capture, usage and storage, as well as projects on the significance of CCUS at system level and for society.

The 2021 agreement on a green transition of the agricultural sector set aside funds for the development of technological potentials, of which the 2022 Pyrolysis Pool of DKK 194 mill. was allocated to the establishment and scale-up of production plants.

The Just Transition Fund focusses on regional and local development and is currently in the process of allocating DKK 196 mill. for further development of pyrolysis in Northern Jutland and/or Southern Jutland. However, the Fund is having difficulties distributing the funds, in part because of the eligibility criteria for the scheme.

Originally, it was also possible to obtain production support for carbon storage with biochar through the NECCS funding scheme (negative emissions from CCS). This was intended as a competitive funding scheme in which the cheapest reductions were eligible for funding, regardless of whether they came from pyrolysis plants, biogas upgrading plants or direct atmospheric carbon capture. The fund was a supplement to the large CCS fund targeted at large point-source emitters.

The funds were motivated by a political desire for measurable impacts in relation to the targets for 2025 and 2030.

Deployment of pyrolysis and CCS with biochar is unlikely to be possible to any significant extent before 2025. Nor is it likely to be possible, at this point, to document the net effects of carbon sequestration with biochar on progress towards meeting the current political targets, see section 6.5.

NECCS funding scheme for carbon storage

A total of DKK 2.5 bn. was set aside in the 2022 Finance Act for the NECCS funding scheme (negative emissions through CCS). The pool provides funding for the establishment of a value chain for negative emissions with a view to ensuring capture and storage of what corresponds to 0.5 million tonnes of CO_2e annually from 2025. The pool will provide funding for a period of up to eight years. The funds will be paid as a fixed subsidy per tonne carbon geologically stored.

The funds must go to cover costs of collecting, transporting and permanently storing biogenic or atmospheric carbon. "Biogenic carbon" means carbon formed through incineration, fermentation, decomposition or processing of non-fossil fuels or biomass. "Atmospheric carbon" refers to carbon from ambient air, not carbon from energy and industrial plants. The Danish Energy Agency published the tender documents for tenders for NECCS on 10 November 2023 and the deadline for submission of tenders was 15 January 2024.

The NECCS funding scheme does not subsidise capture and permanent storage of carbon from incineration or from processing fossil fuels or biomass (there is a separate CCS Fund for these). Neither does the fund subsidise negative emissions from non-geological carbon storage (e.g. biochar from pyrolysed biomass) and from non-technological measures (e.g. afforestation).

Sources: Danish Energy Agency (2023).

As a result of the market dialogue in the summer of 2023, CCS with biochar was removed as a technology eligible for funding under the scheme on the grounds that biochar does not result in permanent storage, see the Danish Energy Agency (2023b). The criteria were subsequently adjusted so as to apply to CCS based on geological storage. Biochar is not usually stored underground but instead in the topsoil where nutrients from the biomass will be recirculated.

One way to promote the deployment of biochar capacity in Denmark (in efforts to achieve specific political emission reduction targets, for example) could be to reduce approval processing times through centrally determined standard processes that municipalities can use as the basis for fast-track interpretation, assessment, and processing of the rules before granting approval. This option is possible already according to the current regulations and approval processes. This can be especially challenging for new technologies, because practice and guidance in the area are limited.

Rapid scaling on the basis of existing rules and approval processes will put an extraordinary amount of pressure on municipal capacities.

6.5. The climate impact of biochar in national emission inventories

Although biochar was identified as a methodology with enormous technological potential by political decision-makers in 2021, there is currently no approved methodology for including the net effect of biochar in national emission inventories.

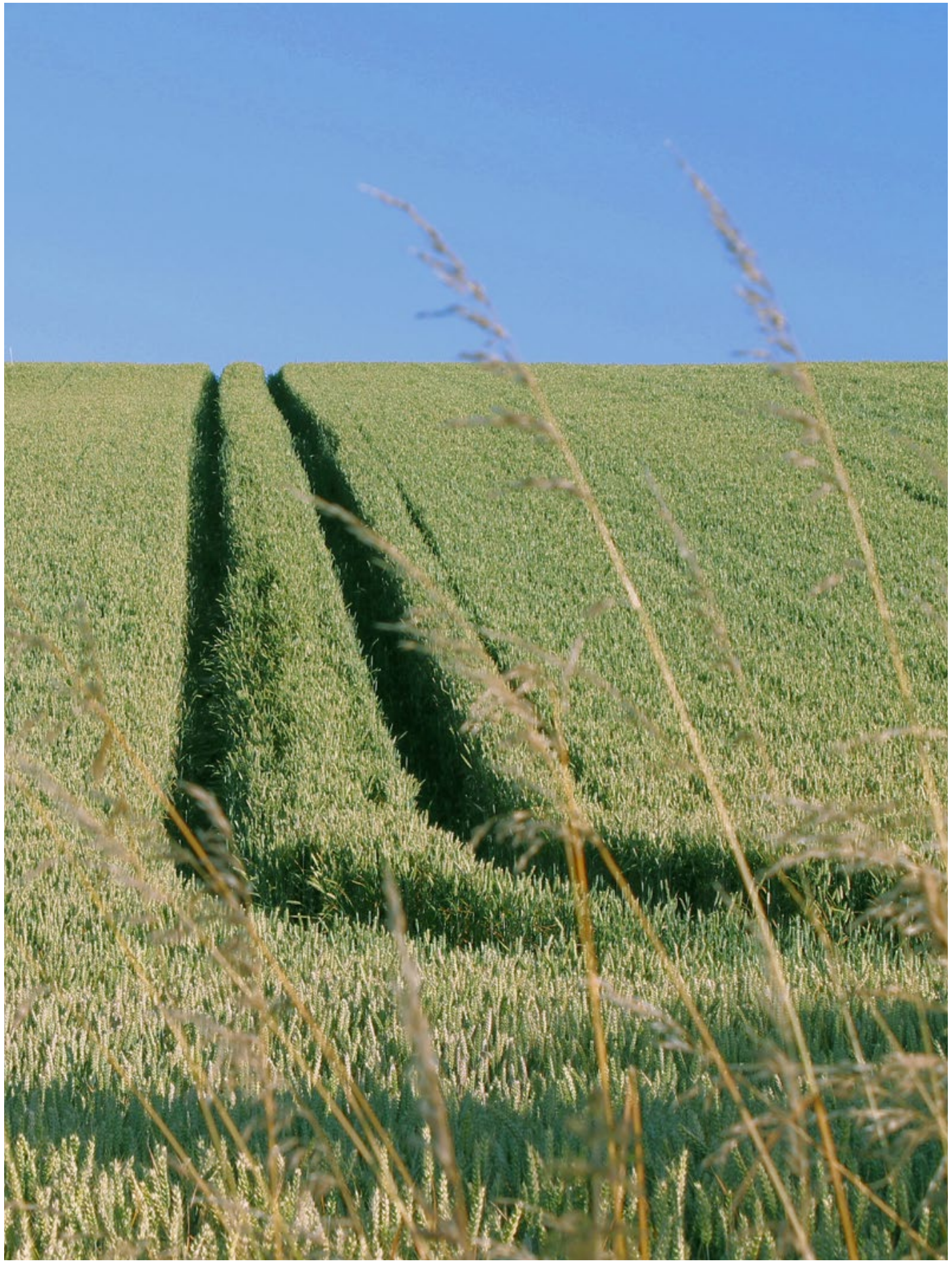
So far, estimates of the potential have been based on preliminary assessments, and the Danish Energy Agency has previously pointed at the need for the development of methods. An ongoing project at Aarhus University to address this is expected to report on results in 2026.

As long as no approved methodology is available for inclusion of the net effect of biochar (relative to the relevant biomass baseline scenario), use of biochar cannot be counted towards emissions removals in national inventories, nor can it be included in estimates of Denmark's progress towards meeting the 70 pct. target by 2030 (including the intermediate target by 2025) and sector-specific targets for agriculture.

However, work to develop a methodology should not stand in the way of applying an otherwise relevant climate measure. This applies even if political focus is on meeting short-term targets.

HOW CAN FAST DEPLOYMENT OF BIOCHAR CAPACITY BE SUPPORTED?

A political call to expand the capacity to produce biochar and use it to store carbon in Denmark requires support for technological scale-up of the technology, and it requires reducing risks and uncertainties in the projects, for example with regard to future revenue streams and cost profiles, as well as case processing times for approval.



How can biochar be made ready for the market?

Chapter 7

Carbon capture and storage with biochar in agriculture requires collaboration across sectors and stakeholders that do not necessarily normally work together. A condition for a financially viable model is that everyone involved has a benefit and incentive to participate. Furthermore, the pyrolysis plant in itself requires a large initial investment and industry knowhow about operations and scaling, placing demands on possible owners and investors.

7.1. Relevant stakeholders

Because biochar can be produced from several different types of input, there are several possible scenarios for a biochar value chain, including with regard to the stakeholders involved in the value chain.

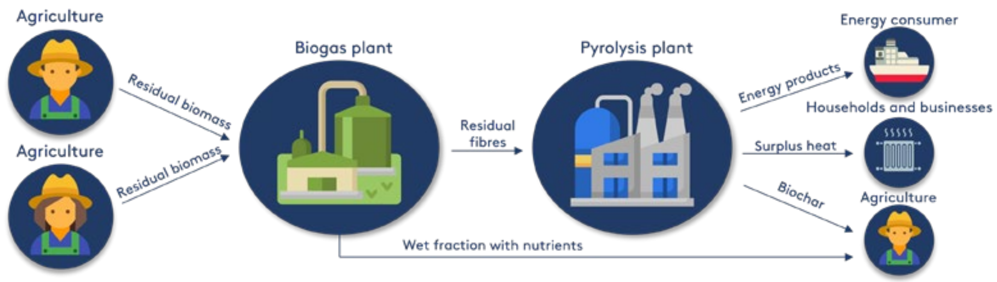
A typical, simplified value chain consists of:
- a supplier of biomass, for example a farm, a slaughterhouse, a wastewater treatment plant
- a pyrolysis plant, which converts biomass to biochar, amongst other things
- buyers of the energy products produced by the pyrolysis plant, for example the energy sector
- buyers of biochar, for example the agriculture sector
- buyers of surplus heat from the pyrolysis plant, for example the industrial sector or households in the form of district heating

The value chain will likely be much longer and more complex in practice. There are potentially more financial and climate benefits by ensuring a circular value chain and exploiting the biomass in as many links as possible along the chain before the biomass is turned into biochar.

This will put the pyrolysis plant at an advantage by offering a final destination for biomass residues that are not being exploited in the existing biomass value chain.

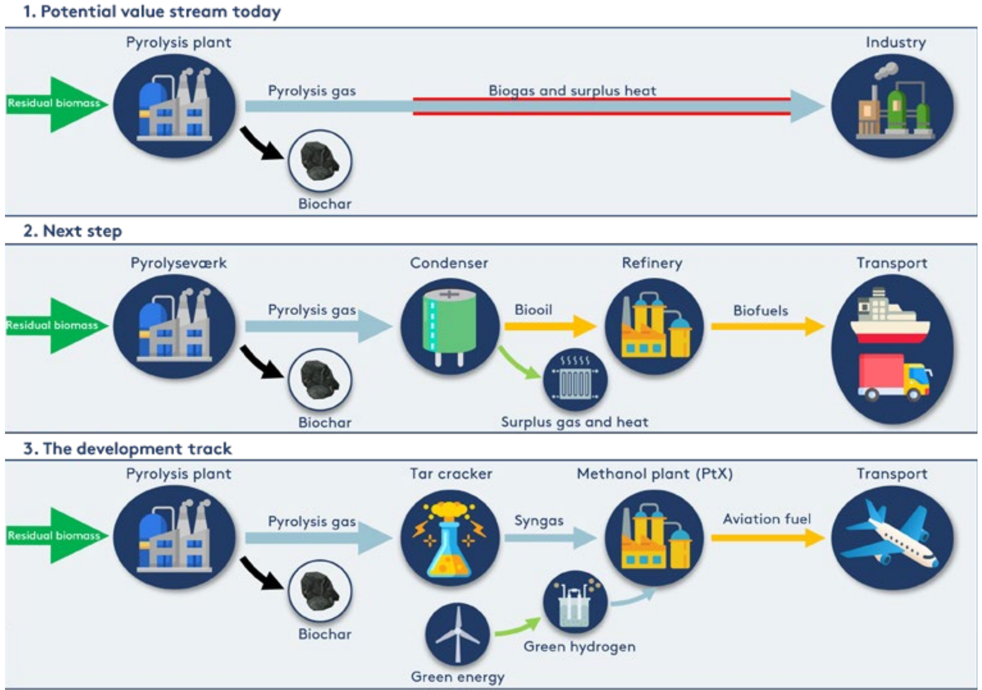
For example, pyrolysis plants can be included in the value chain of biogas plants. Thus, agriculture can supply biomass residues to biogas plants, and after gasification, the

Figure 7.1: Example of value chain with biogas plant



Source: The CIP Foundation's own graphic

Figure 7.2: Examples of value streams for the pyrolysis gas



Source: The CIP Foundation's own graphic

biogas plants can separate the remaining biomass into a liquid fraction and a fibre fraction. The liquid fraction can be used as a fertiliser product in agriculture, and the fibre fraction can be used by pyrolysis plants in the production of biochar and energy.

Just as the value chain before the pyrolysis plant can be expanded, so can the subsequent process.
The pyrolysis gases produced in the pyrolysis plant together with the biochar can be used for many different purposes, not least in step with further development of the technology. It will improve the business case in the long term if the plant can eventually produce high-value energy products.

Today, the pyrolysis gas is best used for heating purposes, for example in a nearby biogas plant to upgrade biogas, or to meet the demand for space heating in another nearby industrial facility. The surplus heat can also be used as input in the district heating grid.

New opportunities for exploitation will come in step with technological advances. A next step will be to condense the gas into bio-oils. Bio-oils can be used to produce biofuels and the remaining surplus gas and surplus heat can be used for space heating.

In the longer term, more options will be available, and the gas can be used to produce syngas, for example, which can be further processed with hydrogen to make methanol (PtX) and aviation fuels. However, this requires the availability of green hydrogen and PtX plants.

Biochar production can therefore be established from scratch, or it can be established as a supplement to an existing production setup with biomass residues by retrofitting existing plants, for example biogas plants and food production plants. The specific opportunities therefore rely on the local context, but they are also very flexible and offer major global perspectives for exploiting the technology.

Careful consideration should therefore be given to the biomass supplier and to the ultimate buyer of the energy product when designing the value chain to ensure the best possible value creation and exploitation of opportunities. In the final analysis, what matters are the technological possibilities, the costs and the siting, and we will address these below.

7.2. A sustainable value chain

If biochar production and storage in agriculture is to be profitable, it must be associated with additional revenues for the farm supplying biomass, the pyrolysis plant producing biochar, and the farm buying the biochar.

In simple terms, such revenues can be generated through the sale of the energy products from the pyrolysis process, as these are valuable in themselves. However, to ensure a well-functioning model in which agriculture has an incentive to supply biomass for the process, agriculture must be paid for supplying the biomass and, thus, have a stake in revenues. In some situations, suppliers may be willing to pay the pyrolysis plant for taking the biomass, for example if the biomass is sewage sludge, and this can improve the business case. However, this is not the typical situation.

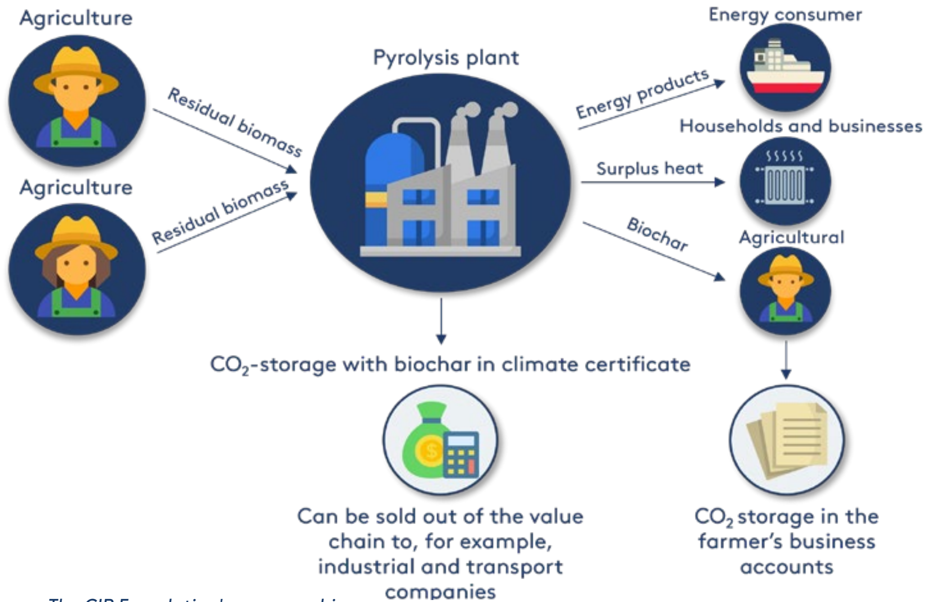
To make a value chain for carbon storage with biochar in agriculture that is sustainable and exploits the potential derived climate and environmental benefits, there must be something to be gained for farmers from applying biochar to their fields. In other words, there must be a market that is willing to pay for the positive climate impacts of biochar.

Such willingness to pay requires documentation of the positive climate impact of biochar, for example carbon removal certificates.

7.3. Climate credits as a financial instrument

By including sales of climate credits in the value chain, the pyrolysis plant will be able to achieve revenues from the production of biochar and subsequent application on fields, which can render the process financially viable.

Figure 7.3: *Value chain with sale of climate credit*



Source: The CIP Foundation's own graphic

In simple terms, agriculture will supply biomass residues to the pyrolysis plant, which will then produce an energy production, surplus heat and biochar.

The biochar means that a climate credit can be issued, which the plant can sell off to an industrial or transport company that needs it to reduce the climate footprint of its products. The sale of the climate credit provides the pyrolysis plant with income from its biochar production.
However, if the biochar is applied to fields, for example, farmers must have a benefit from doing so. This benefit could be direct payment from the pyrolysis plant and/or a share in the climate credit, which can be sold off or used to compensate for the farm's own carbon emissions. In other words, a sort of profit-sharing.

As opposed to a scenario without climate credits, in a scenario with climate credits the produce that a farmer sells to a food company will not have a lower climate footprint if all of the climate credit is sold. Instead, it will have the same climate footprint as if no biochar had been applied to the field, because the climate effect of biochar has been sold off as a climate credit. However, the carbon storage can still be counted towards the farm's carbon accounts. Offering carbon removal certificates for sale on a trading platform facilitates the highest market price for the climate initiative. It also allows farmers the opportunity to keep the carbon removal certificate, and thus the climate benefit, in their own production chain if their willingness to pay is greatest.

If it is not possible to pay agriculture appropriately for storing the biochar, it will still be possible to exploit the carbon storage potential by storing the biochar in other ways, for example by incorporating it in building materials.

However, in this case agriculture will miss out on the environmental benefits of spreading biochar on agricultural soils. Such missed benefits include better water retention properties, less nitrate leaching and runoff to nearby watercourses, etc.

An alternative, or supplement, to selling climate credits would be to subsidise carbon storage with biochar at political level, for example through a start-up subsidy scheme aimed at establishing a market for biochar.

7.4. Relevant co-locations

The location of pyrolysis plants plays an important role and can potentially generate co-location benefits that will improve the businesses case and plant finances.

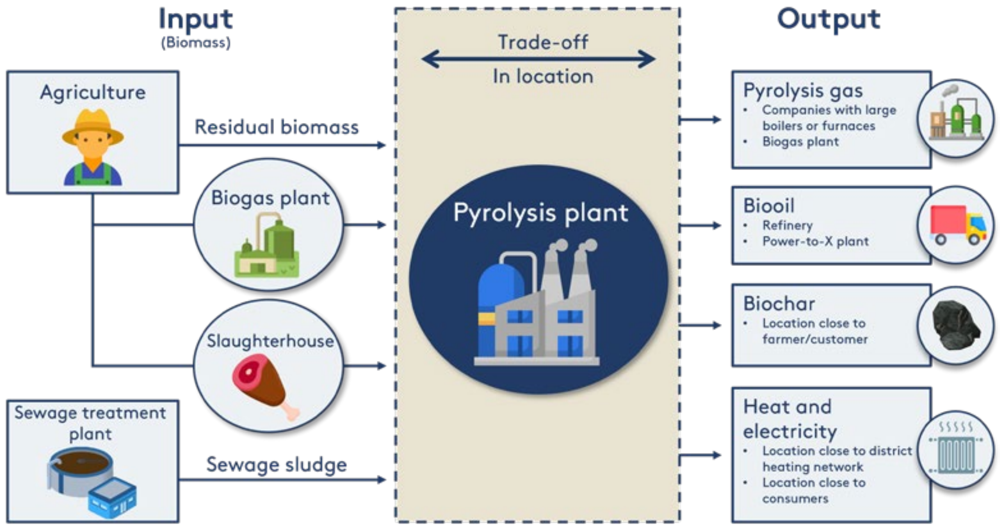
These gains arise if there are financial benefits or efficiency improvements from locating the pyrolysis plant near input suppliers, output buyers or relevant infrastructure.

The advantages could pertain to logistical benefits from lower transport costs and synergy effects achieved because a co-located plant will be able to exploit by-products, residual products or surplus heat, and this can increase the plant's total efficiency and energy utilisation.
An important factor when siting pyrolysis plants is the viability of long biomass transport distances.

Wet biomass contains large quantities of water and is therefore expensive to transport, and the dry-matter left for the pyrolysis process is relatively small. Locating the pyrolysis plant close to the biomass source is therefore preferable in terms of optimising logistics and lowering transport costs. Alternatively, the biomass can be dried at the place of origin and turned into pellets for easier transport.

However, there are also benefits from siting the pyrolysis plant near to where there is demand for biochar and side streams from the pyrolysis process in the form of surplus heat and bio-oil, for example. This can be achieved by siting the pyrolysis plant near to the district heating grid, making it easier to exploit the surplus heat from the pyrolysis process.

Figure 7.4*: Example of trade-off in relation to co-location benefits*



Source: The CIP Foundation's own graphic

However, it will not always be possible to locate pyrolysis process production close to both buyers and suppliers in the biochar value chain. In the final analysis, the size of the respective co-location benefits will have to be considered to determine the most optimal location for the plant.

In practice, a decisive factor will be what is more difficult and most expensive to transport. The biochar itself is relatively easy to transport.

So, the decision will rely more on the energy products produced and, in particular, on the type of biomass used. The biomass will often be decisive because, in many situations, it will not be financially viable to transport the biomass across long distances. A way to minimise the transport distance between the biomass source and the plant is to have many small pyrolysis plants.

However, pyrolysis plants are technically demanding to operate, and they therefore need to be of a certain capacity to ensure professional management of the plants, economies of scale and to keep operating expenses down.

For more, see the CIP Foundation's background memo on business models and value chains for biochar (2024d).

7.5. Ownership and investors

Pyrolysis and biochar production is still in the upstart phase in Denmark, and anyone can invest in a plant.

However, two major factors are decisive for ensuring optimal ownership.
Firstly, a pyrolysis plant producing biochar typically costs above DKK 100 mill. and requires a large initial investment and solid finances to carry off.
Secondly, pyrolysis plants are industrial plants, and they require considerable industrial knowhow and an industrial approach to standardising and scaling. Similarly, an industrialised party may be required to manage the production and logistics across value chains.

In addition to requirements for the owner, carbon storage with biochar in agriculture requires collaboration across sectors and suppliers that do not necessarily normally work together in other contexts, and that may have conflicting incentives and interests. It is therefore obvious to look at whether the ownership can ensure harmonised incentives.

These challenges in many ways resemble the challenges and considerations previously faced by the biogas sector, and it is therefore relevant to build on experience from this sector.

The biogas sector has gone through an industrialisation process which saw a professionalisation of ownership and a shift from individual farms investing in and running their own biogas plants to companies with large industrial knowhow investing in and running much larger biogas plants. The typical ownership structure consists of a majority shareholder in the form of an energy company and a group of minority shareholders in the form of farmers, who gain a share of any upside in the company through their participation in the ownership.

This has led to considerable economies of scale for the plants, and it has also provided opportunity for external investors such as pension companies and investment funds to invest in the plants and make capital available.

The advantage of letting an energy company or an investment fund become a strong co-owner of a pyrolysis plant is partly that farmers do not have to make the investment themselves, and partly that it brings a stakeholder into the business with extensive insight and industry knowhow, who can deliver the necessary scaling and standardisation.
This will ensure the plant's ability to generate growth is not impaired if there is not enough capital for new investments in new growth-generating initiatives such as installing a district heating pipeline to the plant, carbon capture technology or electrolysis. At the same time, external investment can be crucial in ensuring the necessary deployment of pyrolysis plants if we are to realise the political ambitions.

Including farmers as minority-share owners of pyrolysis plants - cooperative ownership 2.0 - is still an idea worth considering. In this scenario, agriculture has co-ownership against guaranteeing long-term provision of biomass. In this way everyone shares in the upside - whether it be the price of energy or the climate benefit. And the pyrolysis plant has security of supply of the necessary input. This ensures harmonised incentives among all stakeholders and reduced risk for the pyrolysis plant.

Supplies can come from supplier associations, for example. This will make it easier for plants to make sure they have security of supply and increase farmers' negotiating power. However, as mentioned above, everyone is free to invest in a plant, and we will probably see several different forms of ownership, with different business models and plant sizes.

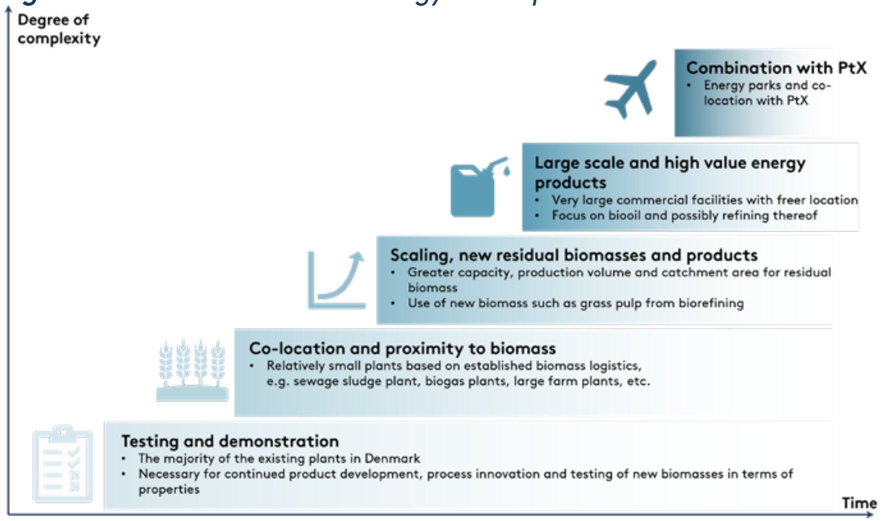
7.6. How will biochar production be expanded?

As described in Chapter 4 above, it is financially viable to invest in biochar production when the production is based on biogas fibres from a biogas plant (co-location), or when biochar is produced from straw residues with bio-oil as a by-product. This business case is financially viable, largely due to the sale of green energy, but also requires sales of climate credits. Sewage sludge is also a financially viable case, but it relies on wastewater treatment companies' willingness to pay for the disposal of the sludge. In terms of scaling, projects have moved from test and demonstration plants to plants ready for commercial production and have therefore moved several steps up the potential development ladder, see figure 7.5.

From smaller plants, able to handle a few thousand tonnes dry matter annually to larger production units of 40,000 tonnes dry matter and potentially up to 100,000 tonnes over time, depending on the availability of biomass residues that can be sourced for production.

From stand-alone plants to plants in co-location with biomass suppliers and potentially also with buyers of energy products in clusters or energy hubs.

Figure 7.5*: How can the technology develop?*



Source: The CIP Foundation's own graphic

The journey of the biogas sector

Around 1975, Denmark saw the establishment of its first farm-based biogas plant, established by a farmer on Funen. Over the following 15 years, other farmers followed the lead and built their own biogas plants.

This development continued up through the 1980s and 1990s, when a number of large biogas plants were established that were cooperatively owned by several farmers. In the 2000s, the development in new plants almost came to a halt.

Not until with the 2012 Energy Agreement did biogas production gain speed again. The 2012 Energy Agreement made it possible to obtain subsidies for using biogas in electricity production or supplying it to the natural gas grid. The agreement also increased the construction subsidies from 20% to 30%

While the finances and technical issues associated with the plants had so far quelled interest in establishing biogas plants, from the late 2010s more and more investors became interested, and this generally led to increased professionalisation and industrialisation of the biogas sector. The majority owner typically became an energy company, a food supplier or similar, while farmers owned smaller shares and had supplier agreements with the company. As revenues from carbon benefits became a possibility, this also became a negotiation element in supplier agreements.

Pyrolyse as a service

A so-called pay-per-use model, or pyrolysis-as-a-service, could be another relevant business model that would allow farmers or wastewater treatment plants not able or willing to invest in plants to benefit from the process.

In this model, an industrial player leases out the plant to a farm or a wastewater treatment plant, for example, which then supplies a certain amount of biomass for the plant and receives a certain amount of biochar in return.

In this model, for example, wastewater treatment plants avoid having to dispose of sewage sludge, which they today do by paying farmers to apply the sludge to their fields.

For farmers, the model is beneficial because they do not have to invest in a plant. The model also leaves ownership of the plant to a specialised industrial player.

Experiences from other countries

Chapter 8

The global market for biochar is in fast development, and biochar production is already up and running in many countries. In other countries, biochar is used as fertiliser and for composting in particular, but also for many other purposes. The many use options and the possibility of CCS is pushing demand for biochar.

8.1. Growing global market for biochar

MANY COUNTRIES ARE AHEAD OF DENMARK

The market for biochar production and trade is in rapid development abroad, while in Denmark the market is still on the drawing board.

The largest players in the global biochar market are the USA and China, followed by northwestern Europe, with Germany as the largest player. Biochar production is also well under way in other countries, such as in Australia, Kenya and India.
In other countries, biochar is primarily utilised for its fertiliser value, but the carbon storage value of biochar is also being discovered by many.

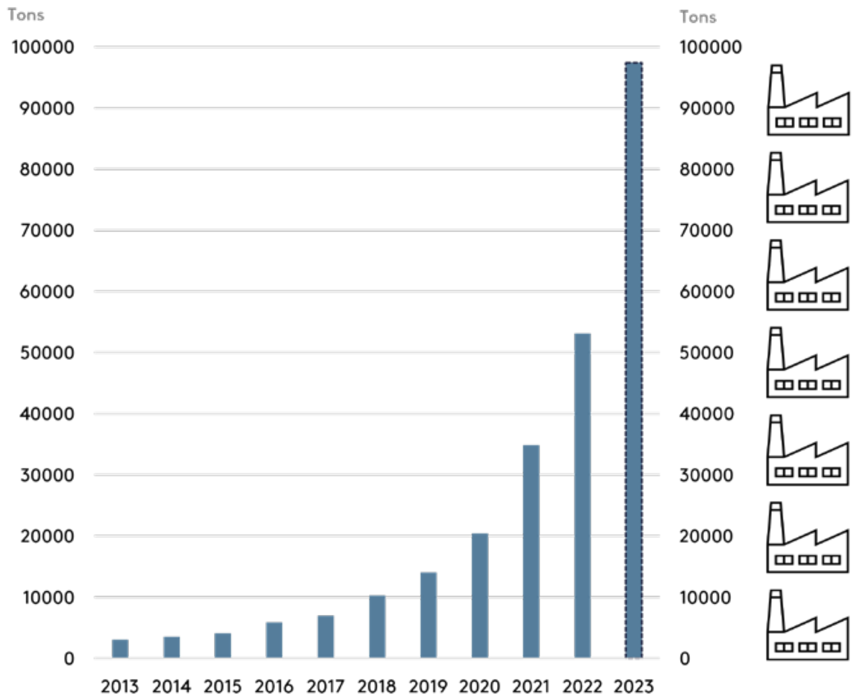
Denmark is therefore by no means a global frontrunner in the biochar market, and using biochar is far from a new thing.
On the other hand, Denmark has the potential to relatively quickly grow into an important player in the biochar market.
According to the European Biochar Initiative, Europe's total biochar production capacity was expected to reach just under 100,000 tonnes by the end of 2023. This is no more than what can be produced by seven of Stiesdal's (Danish climate-technology company) 20 MW plants.

EUROPEAN BIOCHAR PRODUCTION CAPACITY OF JUST UNDER 100,000 TONNES

In 2022, total biochar production capacity in Europe was at around 53,000 tonnes, corresponding to the output capacity of around four 20 MW plants.

It is expected the capacity will increase to just under 100,000 tonnes biochar in 2023, corresponding to the output capacity of around seven to eight 20 MW plants. In comparison, Danish biochar production capacity is assessed at around 30,000 tonnes biochar annually, with carbon storage in the range of almost 45,000 tonnes carbon, see Annex A. The plants under development in Denmark will therefore relatively quickly bring Danish biochar production to the forefront of biochar producers in Europe.

Figure 8.1: Increasing biochar production in the EU, which in 2023 corresponds to 7-8 pct. of 20 MW pyrolysis plants



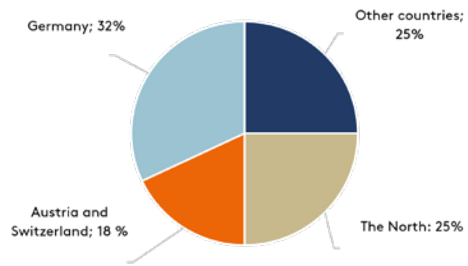
Note: Biochar production from 2013-2022 and expected production capacity in 2023, Europe.
Source: EBI (2023), "European Biochar Market Report 2022-2023"

The increasing biochar production deployment in Europe is also seen at global level. In 2022, a number of research agencies assessed the world biochar market to be worth around USD 200 mill. (DKK 1.4 bn.), and this figure is expected to increase in future.

HOW MANY BIOCHAR PRODUCERS ARE THERE IN EUROPE AND WHERE ARE THEY LOCATED?

According to the European Biochar Initiative, there were around 130 biochar-producing facilities in Europe in 2022. The major part of European biochar production is located in Germany[18].

Figure 8.2: Germany accounts for the majority of biochar production in Europe, at the end of 2022



Source: EBI (2023), "European Biochar Market Report 2022-2023"

18 EBI (2023)

German biochar production accounts for around one-third of total European biochar production, followed by the Nordic countries, which account for one-quarter of total European biochar production, with Sweden as the largest producer. After the Nordic countries come Switzerland and Austria.

8.2. The many uses of biochar

BIOCHAR AS A SOIL IMPROVEMENT PRODUCT IS NOTHING NEW

In other countries, biochar has long been used as a natural means of improving sandy soils and turning them into fertile farmland[19].

People in the Amazon region started using biochar to enrich the soil more than 2,500 years ago. Dry and infertile sandy soils are common in rainforests like those in the Amazon. Adding biochar transforms sandy soil to a darker, more nutrient-rich and fertile soil.

It has been assessed that, in Europe, most of the biochar is used on farms (Scmidt et al., 2021), while in the US, although it is also used primarily for soil improvement, it is also used as a fertiliser product in parks and other green areas, as well as in horticulture and private gardens (Thengane et al., 2021).

However, biochar has many other uses besides as a soil improver and fertiliser. For example, biochar is used as an animal feed additive, in building materials, for metallurgy and in certain health products.

BIOCHAR AS A CARBON STORAGE METHOD MAY BE THE WAY FORWARD FOR BUSINESSES

The central fuel for the expected growth in the biochar market is growing awareness of biochar as a valuable carbon sequestration option.

The relatively new willingness to pay for long-term and documentable carbon storage in the voluntary market for climate credits can help businesses with their carbon emission reductions. In response to increased political focus on the consequences of climate change, there is now a willingness to pay for carbon offsets. This development is the reason industry and transport-sector companies are now buying climate credits to compensate for their carbon emissions.

Because of this global trend, biochar production is now more financially viable, provided the biochar is applied to farmland and, thus, leads to long-term and stable carbon storage that can be sold as a climate credit.
The European Biochar Initiative assesses that around 70 pct. of biochar production in Europe is certified and therefore can be sold as climate credits.

All in all, looking across countries, the underlying incentive for implementing biochar may therefore differ. The incentive to implement biochar in Denmark is driven more by its carbon storage value than is typical abroad.

MANY DIFFERENT TYPES OF BIOMASS RESIDUES AS INPUT FOR PYROLYSIS

Just as there are differences in the effects that can be achieved from using biochar, there are differences in the types of biomass residues used to produce the biochar. The choice often depends on what types are available in the respective countries.

In the US, western Europe and Australia, biochar is most often produced from wood chips and wood residues, livestock manure, straw residues, etc.
In Asia and other developing countries, biomass residues primarily comprise rice straw or rice husk, nut shells from cocoa plants, palm leaves or bamboo.
There are generally plenty of relevant biomass residues available in the world for pyrolysis. Common for all biomass residues used for biochar is that they are leftover products that would otherwise not have had any financial value.

8.3. What can Denmark learn from other countries?

IN MANY COUNTRIES OUTSIDE DENMARK BIOCHAR IS NOT A NEW PRODUCT

Several companies work with biochar in different ways and the uses of biochar differ.

It appears that biochar is not that new outside Denmark. For example, biochar is sold as a fertiliser product to consumers in the USA and China. In the US, biochar can be found on the shelves of DIY centres such as The Home Depot. Furthermore, in China, garden fertiliser products and actual pyrolysis plants are available for sale on the Alibaba online wholesale marketplace.

Free biochar in Stockholm

In Stockholm, there is a programme that collects garden and park waste and coverts it to biochar. Citizens can then collect biochar for free at recycling centres for use in their gardens. The biochar is also sold to local authorities for use in public parks and gardens, etc.

Source: Stockholm Biochar Project | Nordregio

Sweden has a programme that makes it easier for citizens to use biochar, see example below.
In other places in Sweden, companies have surplus heat themselves. This applies to paper manufacturers or food manufacturers, for example, see example below.

Swedish food company manages the entire value chain itself

An example of this is the Swedish food manufacturer Hjelmsäters Egendom, which uses German pyrolysis technology to turn residual products from seed production, for example, to make biochar for use as soil improving fertilisers in seed production.

Source: Biochar in Sweden, Hjelmsäters Egendom | Puro.earth

There are other biochar uses, for example within building and construction. In Sweden, Biokolprodukter Global AB sells cement and concrete products with biochar to reduce the climate footprint of concrete, which otherwise has a very considerable climate footprint. There are also other positive benefits of adding biochar to cement and concrete products, such as improved flexural and tensile strength.

Another example is the American company Solid Carbon, which produces concrete admixtures with biochar. In June 2022, Solid Carbon poured a 5,000 square-foot carbon-negative concrete slab in Dayton, Oregon, in the US, sequestering the equivalent of over 5.1 tonnes of CO_2 in the floor of the Remy Wines Winery.

There is also the Norwegian company, Vow Green Metals, which uses biochar for metallurgy. Biochar resembles coal and coke, which are used for heating in the steel industry to melt iron when making alloys. Replacing the fossil alternatives with biochar reduces the climate footprint of the heating process. There is no carbon storage involved,

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but instead the climate footprint is reduced by displacing fossil fuels.

US ONLINE PLATFORM GUIDES USERS ON THE RIGHT BIOCHAR PATH
Getting started producing and selling biochar can be a mouthful for those with no previous knowledge in the area.

Cost-benefit analysis in the US

It can be difficult to determine what is the best type of biochar for a specific type of soil, and what effects can be achieved from applying biochar. In the US, they have made a guide to help users in this process. The guide is available on the Pacific Northwest Biochar Atlas platform. The platform offers cost-benefit analyses of the use of biochar, for example.

Source: Biochar Cost-Benefit Analysis Tool

In the US, they have therefore established an online platform to guide users in the right direction when considering using biochar.

LEGISLATION BASED ON CARBON REMOVAL CERTIFICATES
Denmark can also find inspiration from Switzerland for how to approach drafting appropriate legislation and guidelines on biochar production in a way that is simple and easy.

What they have done in Switzerland is simply turn an existing voluntary standard into legislation. The biochar must be certified according to the EBC's (European Biochar Certificate) guidelines, which are based on research results from the Ithaka Institute for Carbon Strategies.

EXAMPLES OF FUNDING FOR BIOCHAR DEVELOPMENT IN OTHER COUNTRIES
There is no EU funding programme aimed directly at biochar and pyrolysis. Nonetheless, there are several examples of EU-funded biochar products, as it is possible to obtain funding through other EU funding programmes for climate projects and research and development projects.

Tierpark Berlin, for example, received EU funding in 2017-2020 for its CarboTIP project. The project transformed biomass collected at the zoo into biochar. The biochar was tested for its fertiliser properties, carbon content and more. The funding came from the EU's European Regional Development Fund[20] through Operational Programme 'Berlin'.

Furthermore, Carbo Culture, a Finnish company, received funding of EUR 2.16 mill. from the European Innovation Council (EIC) in 2022[21]. The funding was awarded from the EU's Horizon Europe programme to develop Carbo Culture's new plant.

Looking outside the EU, Black Bull Biochar (BBB), a British start-up, in July 2022 won a GBP 3-mill. government contract to develop a digital B2B platform. The platform unites agricultural, industrial, and research partners in order to scale the use of biochar.
Also, the USA has a funding programme for biochar producers, called "Soil Carbon Amendment (336)". The programme is financed by the USDA Natural Resources Conservation Service (NRCS).

According to the US Biochar Initiative (USBI), the programme covers around 75 pct. of the average costs of eligible projects[22].

All in all, it appears that several countries have come further than Denmark in the development of the biochar market. However, this does not mean that Denmark has no chance in the market. Denmark will be able to increase its market share relatively fast if more commercial plants are established like those produced by Stiesdal or other Danish pyrolysis producers such as AquaGreen or MASH Makes.

THE CIP FOUNDATION IS LOOKING INTO THE OPPORTUNITIES FOR EXPORT OF DANISH BIOCHAR
With an analysis expected to be completed in early 2024, the CIP Foundation is looking into the opportunities for Danish biochar.

20 EU COMMISION (2019)
21 EU COMMISION (2022)
22 Smith, B., Loll-Webster, J., Gray, M., Seman-Varner, R. (2023)

What are the next steps?

Chapter 9

Marketisation of CO_2 storage in biochar requires developing the necessary regulation, establishing new value chains and stakeholder cooperation. It also requires translating research and knowledge into practice-oriented guidance.

9.1. Status of progress for biochar in Denmark

With this status report and underlying analyses and documentation reports, as well as through seminars and stakeholder engagement, the CIP Foundation has looked into the opportunities for marketisation and use of carbon storage with biochar as an important climate measure for Denmark and Danish agriculture.

Considering the "cogs" presented in Chapter 2, the following takes stock of the market opportunities for biochar in Denmark.

The technology behind biochar is almost ready for commercial deployment and scaling (TRL 8). After this, there will likely be a period of learning, continued innovation, fine tuning and simplification of processes, as well as more standardised manufacturing of pyrolysis plants with resulting lower initial costs. This involves increased production at still lower unit costs.

The biomass residues are there. Biochar must be produced from the biomass residues available in the local area, but these can be any type of biomass residues, from plant residues to livestock manure and deep litter, residual products from various production products, marine biomass residues, garden and park waste, and sewage sludge.
The business case is there. The market players must come together from throughout the value chain to establish sensible, cross-cutting supplier agreements and buyer agreements, which factor in the costs of storing the carbon.

Biochar and carbon storage are also a good investment socio-economically, and with a very low displacement cost, depending on how many side-effects and potential revenues from climate credits are included in the estimate.

In agriculture, biochar will be in demand as a fertiliser product, but biochar will also be in demand for use in other products, such as building materials, in order to reduce the climate footprints of these products. Although biochar is perhaps in particular demand because of its ability to store carbon, there must first be an actual biochar product and biochar use before a climate impact can be documented via a carbon removal certificate.

However, this is where the existing regulatory framework becomes an obstacle, as there is no legal basis for using biochar made from agricultural residues. Furthermore, the existing rules also contribute to dragging out the process of establishing pyrolysis plants close to where the biomass can be sourced. The legislation fails on many points to consider what biochar actually is and what approval processes are required.

The research-based knowledge is growing and must be developed further in step with technological development and marketisation. Research-based knowledge, development of appropriate regulation, as well as development of the market must go hand in hand. It is important that all aspects are dealt with, so that one unresolved aspect does not impede resolution of another. As with other new markets, time will offer new insights and it is important to act agilely and make adjustments along the way.

9.2. Is it realistic to store 2 million tonnes carbon with biochar by 2030?

The analyses by the CIP Foundation offer a basis for assessing the possibilities for meeting the goal of storing 2 million tonnes CO_2e by 2030 set out in the agreement on a green transition of the agricultural sector.

The goal looks attainable on many parameters. On other parameters, certain conditions must be fulfilled. And then there are some parameters which mean the goal is not realistic as things are today. These parameters must be acted upon.

See table 9.1 for details.

LONG LASTING REGULATION- AND ESTABLISHMENT TIME AS OBSTACLES FOR POLITICAL GOAL

The greatest challenges or obstacles for reaching the goal are related to the existing regulation and the time factor; that is, how fast deployment of more production capacity can take place. Moreover, these two factors are connected.

As long as there is only a legal basis for using biochar produced from sewage sludge, and not biochar produced from agricultural side streams (see Chapter 6), there will be no willingness to invest in the deployment of new plants for these types of biomass. Market players need guarantees that they will be able to sell the biochar and realise carbon storage potentials before they decide to invest in these relatively investment-heavy pyrolysis plants.

Although there is the option to obtain temporary, plot-specific approvals (Section 19 approval), this is associated with a considerable risk in relation to future sales prospects, and the capacity deployment required to meet the political ambitions is therefore unlikely to happen.

INVESTMENT DECISIONS REQUIRE CLARITY ABOUT CONDITIONS

Potential investors in pyrolysis and biochar with carbon storage need clarity about a number of conditions, about buyer agreements and about approvals before they are willing to make a final decision to invest.

Table 9.1: Can the political goal of 2 million tonnes of CO_2 storage be achieved in 2030 with biochar?

Question	Elaboration	Question	Elaboration
Is there enough feedstock? ✓	The biomass residues identified as available today mean there are net quantities enough to meet the political goal of 2 mill. tonnes carbon storage per year. Det Nationale Bioøkonomipanel has pointed to a development potential of known biomass of +8 mill. tonnes dry matter up to 2030. In addition to this, there are biomass residues from the sea, forestry residues and residues from other production processes, e.g. grass pulp from biomass refining.	Is it financially viable to make and use biochar? (✓)	The business case behind production and use of biochar is profitable, but it depends on payment for carbon storage, e.g., through a climate credit, through payment for accepting biomass (for sewage sludge), or through subsidies for carbon storage.
Is there enough agricultural land? (⊖)	The current phosphorous cap for application of fertiliser products limits the use of biochar based on digestate, manure, etc. With the quantities of biomass already identified, meeting the goal will require application on around half of all Danish agricultural land every year. The phosphorous cap is restrictive because biochar releases phosphorus over time and not immediately after application.	Is there enough demand for climate credits? (✓)	Internationally, climate credits corresponding to 0.3 mill. tonnes of carbon storage were sold in 2022. The market must therefore be significantly scaled up if the total amount of biochar produced in Denmark alone will account for 2 mill. tonnes carbon in 2030. However, several large companies that have set themselves climate targets, need long-term and reliable carbon storage to offset their emissions. And the atmosphere/the Paris target requires net carbon sinks for a very long time. In the start-up period, it may be necessary to supplement the market for climate credits as co-financing for carbon storage.
How many plants will be necessary? And can they be built and be in full operation by 2030? ⊖	Based on 20 MW plants, 2 mill. tonnes of carbon storage annually will require production from 70-90 plants. This will require a disproportionately large deployment of pyrolysis plants in a short span of time (6 years) and is not possible by 2030. Over time, the technology, processes, and plants will be more efficient, and this will reduce the deployment needs. The goal can be reached over a slightly longer time horizon, and the technology has long-term relevance beyond 2030.	Is it a good socio-economic investment? ✓	Biochar is a good socio-economic investment, and the displacement price per tonne of carbon is very competitive with other methods of CCS.
Is the legislation ready? ⊖	There is currently no legal basis for use of biochar made from agricultural side streams on farms, and there are no threshold limit values on the contents of harmful substances, etc. in biochar when used as a Danish fertiliser product. Lack of decisions regarding environmental classification of pyrolysis plants (technical installations) and regarding location options in rural zones impede further deployment. Major investment decisions for market deployment are unlikely to be made, given uncertainty and local variation in the framework conditions, and given that it is not possible to establish buyer agreements in advance.	Are there rules for how biochar can be used? ✓	Rules for spreading biochar on agricultural land as a fertiliser product (methods, times of year, etc.) and for documentation of this in fertiliser accounts are in place. The building regulations contain requirements for a number of building materials, and these are supported by standards and guidelines from the Danish Standards Association and the Danish Building Research Institute.

Uncertain conditions translate directly into higher costs to hedge off risks, and this can be decisive for whether an investment is viable.

Many of these processes are unnecessarily time-demanding under current legislation. This is largely because biochar and pyrolysis have not been considered in legislation, and because approvals require taking a "legislative detour" or local, case-by-case basis decisions. See Chapter 6 for more.

The existing regulation therefore affects the establishment time and, thus, the rate of deployment. It is crucial that regulations become clearer about biochar and that approval processes, etc. are optimised in terms of processing times, so that the resulting total establishment time is reduced.

Based on the technology available today, meeting the 2-million-tonne target would require establishing around 70-90 20-MW plants (currently the largest plants available). The technology will be improved and will become cheaper over time. However, even if all that was needed was to establish 40-50 plants of the type, connected in series at a location with large amounts of biomass available nearby, it will still be difficult, also technically, to both realise the deployment requirement and test and scale the production to full capacity by 2030.

Finally, even if everything else is in place, there remains the matter of whether there will be enough agricultural land on which to apply the biochar. Biochar contains a concentrate of the nutrients that were in the original biomass. Based on the current cap

What is standing in the way of progress?

- No legal basis for the use of biochar in agriculture
- A need for a production standard and threshold limit values for harmful substances, etc. in biochar
- Limited experience with scaling and mass production of pyrolysis plants
- Lack of knowledge about biochar among investors and farmers
- A need for more research-based knowledge and better classification of possible effects

What is leveraging progress?

- A global need for CCS at cost-effective prices
- A need for green energy to supplement the more intermittent renewable energy sources (IRES)
- Ambitious climate targets at EU and Danish levels, including for emissions by agriculture
- EU regulation on biochar as a fertiliser product and a standard for carbon removal certificates
- Exploitation of biomass residues (side streams)
- A carbon tax on emissions

on phosphorous, biochar from phosphorous-rich biomasses can only be used to limited extent. However, biochar will not release the phosphorous as quickly as it is released from fertiliser residues applied directly to agricultural land. So, this means the rules may pose a hindrance in this context. The solution may be to introduce a phosphorous cap specifically for biochar.

The possibility of redistributing the phosphorous reserve with biochar is also one of the benefits for society of using biochar as a fertiliser instead of importing phosphorous, which is a scarce resource globally.

ACTION AND TARGET ADJUSTMENT
There are many favourable circumstances for the biochar business case. However, the political 2030 target for biochar is not realistic under the current conditions.
Action is needed. And the timetable needs to be adjusted to reflect an accelerated deployment.

Biochar will also be relevant after 2030 and up to the more distant goals of climate neutrality in 2045 and net-negative emissions in 2050 for Denmark as a whole.

9.3. What is pushing market development forward, and what is holding it back?

The market for biochar and carbon storage is being pushed forward by political pressure as well as by demands for cost-effective climate measures and increased production of green energy to propel the green transition without harming the environment or causing negative land-use changes.

NEED FOR GREEN ENERGY, SECURITY OF SUPPLY AND A SUPPLEMENT FOR VOLATILE SOURCES OF RENEWABLE ENERGY
Pyrolysing biomass residues is a multipurpose process that provides various different products and environmental services:

- Green energy in the form of pyrolysis gas, bio-oil and surplus heat
- Positive climate impacts in the form of carbon storage, avoided emissions and fossil-fuel displacement
- Various environmental benefits depending on the specific use, for example in the form of soil improvement, redistribution of the phosphorous reserve, improved composting and increased resilience of the soil to climate change

Pushing in favour of biochar is also the fact that it is based on biomass residues that have gone through cascading (i.e. sequential and consecutive use of resources) and no longer have any other important economic use. Therefore, the pyrolysis process utilises end-of-waste biomasses and niche resources, giving biomasses new value and creating a new source of income.

Biomass residuals will likely be a scarcer resource in future, and it is important that future energy production does not cause negative land-use changes. The process behind biochar can work with residual products and can supply green energy as a supplement to the more intermittent renewable energy sources.

In the long term, pyrolysis will also be a relevant technology in PtX production, because PtX involves capturing biogenic CO_2 that can be further processed together with green hydrogen. The technology is therefore also future-proof in the sense that it can be a link to the energy system of the future.

INTERNATIONAL PUSH FACTORS
The Paris Agreement's goal to curb the global temperature rise requires deploying many different climate measures, and the UN IPCC has recognised carbon storage with biochar as an important storage technology with global potential. Cost-effective climate measures that can be deployed globally are crucial.

Also, the EU is pushing for the use of biochar for carbon storage and has set ambitious climate targets, including for emissions from agriculture. These targets will guide much of the political development and various programmes.
More specifically, the EU is the first to have recognised in legislation biochar from agricultural side streams as a fertiliser. The EU has also established CE marking for biochar used as fertiliser to support the border trade in biochar within the EU. Denmark must comply with EU Regulation, unless special considerations in its national legislation, such as environmental protection legislation, dictate stricter regulation.

The EU is also leading the way in developing a certification framework for carbon removals to guide the carbon removal certificate market forward. Currently, the most popular carbon storage solution sold in the growing global market for climate credits is biochar.

INTERNATIONAL PULL FACTORS
However, there are also international trends that can impede the biochar market.

The EU, for example, will soon make a decision regarding the duration of various carbon-storage methods, and biochar will likely either be classified as a nature-based technology with a relatively short storage horizon, or as technological storage method, like BECCS and DACCS, with a very long storage horizon. The EU will base its assessment on research results, but there is also considerable lobbyism from multiple stakeholders. The final decision will be normative for how the private market for climate credits will assess the various storage methods in future, and this will obviously influence the future financing opportunities for the technology.

In terms of research, there are many publications about biochar and the potential side-effects of its application, but these publications can be difficult to use for guidance. There is only limited familiarity with carbon storage with biochar, including among potential investors.

Finally, the world is making the technology more efficient, upgrading and scaling it, but there is still only limited experience with mass production of pyrolysis plants.

DANISH CONDITIONS THAT HELP PROMOTE THE MARKET

Like the EU, Denmark has set fixed, political climate targets; for agriculture, there is even a reduction target in the Danish Climate Act. The Danish 70%-by-2030 target, the net-zero-by-2045 target and the negative-emissions-by 2050 target will require considerable emission reductions, but they will also necessitate carbon storage solutions.

Danish politicians have demonstrated their willingness to use technological solutions to meet climate changes, and to promote the market through large funding schemes for point-source carbon capture and storage in depleted oil and gas fields in the North Sea.

The government has also prepared the market for biochar by defining the regulatory framework for how biochar may be used as a fertiliser product, with rules concerning application methods, application times and documentation requirements. Everything is ready at the starting block. Now a legal basis for using biochar is all we need to push out of the starting block.

The Danish market for biochar is characterised by diverse producers of pyrolysis with slightly different technological approaches and these use different types of biomass residues as input. Together they have relatively broad experience, considering the market is still in its start up phase and the market players are SMEs. Furthermore, there are established technology companies in other countries with more experience. This is a good foundation for continued innovation and competition within technology development and scaling options.

Denmark can benefit from previous experience from development of the Danish biogas sector, in which farmers and energy producers are already working together. There is not the same need for a subsidy scheme or the same type of buyer agreements that used to be the norm in the biogas sector, but the biogas sector has experience with capacity building and scaling, with funding models, and with optimising the regulatory framework, for example, to make it possible to site energy plants in the rural zone.

Finally, a Danish carbon tax on agriculture will indirectly promote carbon storage with biochar because it will promote demand for climate measures in general, and because biochar offers agriculture an extra source of income, which can be invested in the green transition.

DANISH CONDITIONS THAT IMPEDE THE MARKET

As mentioned above, a legislative position with regard to biochar is pending, including establishing a legal basis for the use of biochar produced from agricultural side streams. To account for environmental protection concerns, the legal basis should be accompanied by threshold limit values for the content of harmful substances, etc. in biochar.
Furthermore, several approval processes were not originally intended for biochar and pyrolysis and therefore currently require decisions on a case-by-case basis at local level. This prolongs the process unnecessarily, it is knowledge and resource demanding for the individual municipality, and it creates a risk of inconsistent enforcement of the rules.

9.4. Recommendations

Marketisation of carbon storage with biochar, which can also deliver on political climate targets, requires a collective effort. Policy makers must ensure the right regulation and framework conditions, market players must encourage and establish collaboration, producers must scale up production and streamline processes, and researchers must produce reliable knowledge and guidance on the use of biochar in different areas.

A VISION FOR THE BIOCHAR MARKET

Denmark has the potential to exploit its biomass residues efficiently and sustainably, including, as a final step, convert it into biochar and exploit it for green energy and carbon storage at a scale that can offset carbon emissions from agriculture and from other unavoidable emissions.

Stakeholder collaboration in the value chain needs to be systematised, the technology needs to be streamlined and scaled and other biochar applications need to be brought into play.

THREE MAIN RECOMMENDATIONS

The market for biochar should develop through a combination of regulatory pressure and regulatory options, market-driven financing of carbon storage and more reliable knowledge about effects.

Firstly, there must be a clear legal basis for using biochar. If biochar is to be a real solution for farmers, farmers must be allowed to produce biochar from agricultural residues and use biochar for agricultural purposes. The legal basis must be accompanied by threshold limit values for biochar contents, and these limit values should be incorporated into standard tests in the production. Drawing on existing legislation, as a precautionary measure the limit values could initially reflect the most stringent limit values across national and international regulations.

Secondly, in the market start up phase, it is important to secure certainty that the costs of carbon storage can be recovered. Although the market for trade in carbon removal certificates is growing and could eventually finance the costs of establishing carbon storage with biochar, CCS subsidies should be made available on a par with other technology for a temporary period to encourage rapid scale up. Even though carbon storage with biochar is a good idea for society as a whole, the benefits are not distributed evenly, nor to those occuring the costs of the process.

Thirdly, technological developments and use of biochar in practice should be monitored by researchers to update and strengthen the knowledge base over time and to guide the development of appropriate framework regulations. Furthermore, the knowledge base should be systematized and categorized so that it can form the basis for guidelines on the use of biochar.
See table 9.2 for an overview of what can

support a market for carbon storage with biochar in Denmark.

WHO WILL INVEST IN BIOCHAR

The total biochar package, requiring some initial costs but with energy production and positive climate and environmental impacts, is likely to be an attractive investment for several types of investors. These could be pension funds with a sustainability profile looking to make long-term energy system and infrastructure investments to achieve positive climate impacts. Or energy companies that can see the potential in co-locating their production with biochar production, companies with large amounts of biomass residues, food and fuel producers looking to reduce the climate footprint of their products, as well as farmers themselves, municipal wastewater treatment plants, and many more.

WHAT IS THE NEXT STEP?

The 2021 agreement on a green transition of agriculture announced an upcoming strategy for realisation of the technological potential for carbon storage with biochar; that is, an actual pyrolysis strategy, with up-to-date estimates for the carbon storage potential and with specific scenarios for how to realise it.

The strategy was planned for release in autumn 2022 but was delayed due to parliamentary elections and is now expected to be released in early 2024. Furthermore, the Expert Group on a Green Tax Reform is expected to submit proposals for a model for a carbon tax on agriculture. Incentives for climate action in agriculture should be considered in light of the upcoming pyrolysis strategy and CO_2 tax proposal. In their final, politically negotiated form, they will set the framework for the biochar market in Denmark, as well as for the development opportunities for carbon storage with biochar.

The CIP Foundation is monitoring developments and will reassess the market opportunities in its ongoing focus on biochar.

THE CIP FOUNDATION IS LOOKING AT EXPORT OPPORTUNITIES

Carbon capture and storage with biochar is not a technology preserved for Denmark, Danish agriculture and Danish companies in general. It is very relevant for other countries as well. In 2024, the CIP Foundation will therefore look at opportunities for exports of Danish biochar technology and carbon storage business models.

Denmark must be a European frontrunner in the market development of green solutions that are profitable, implementable, and scalable to the resources of the individual country.

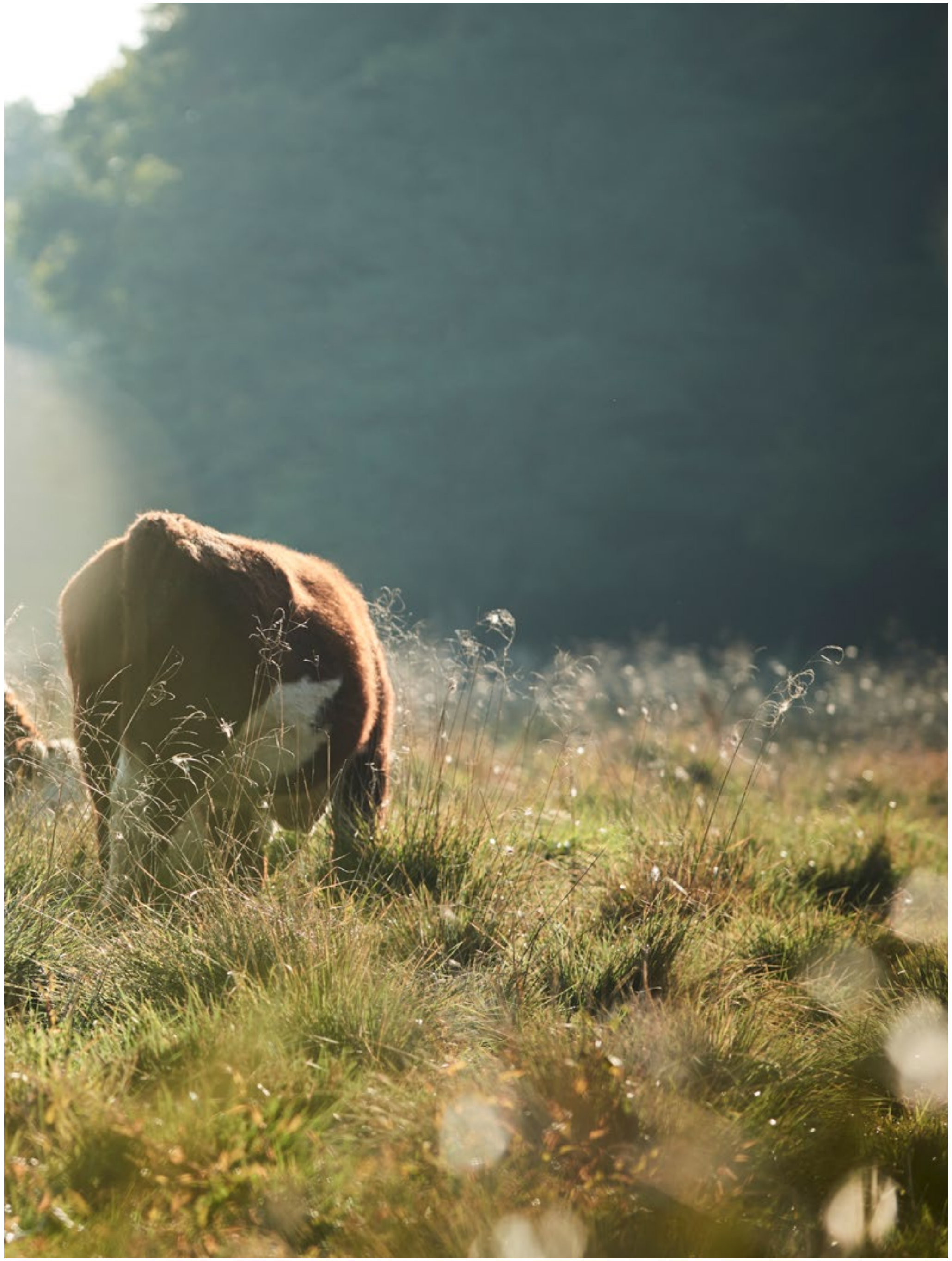

Table 9.2: Recommendations from the CIP Foundation to promote biochar as a way of carbon storage in agriculture

	Regulator	Market players	Researchers and experts
Central recommendations	Establish a legal basis for biochar made of agricultural residues.	Support the start-up with CCS subsidies; to be replaced by the market for climate credits.	Develop guidelines for the use of biochar in agriculture.
General recommendations	• Start with **framework regulation** and **limit values** for the biochar contents, based on the strictest current limits across different regulation and by applying a prudence principle, which can be tightened or relaxed in line with new knowledge. • **Inter-ministerial task force** with focus on authorisation and process simplification for quicker establishment of biochar production. • Develop **method to calculate net CO_2 storage** with biochar in the national emission inventories, so that storage can also be recognised and included in political objectives. • **Identify relevant areas for pyrolysis plants** in combination with current municipal projects to identify suitable areas for biogas production and energy parks for quicker establishment.	• Spread **awareness among potential investors** to accelerate interest in the technology. • Establish logistics chains with the possibility of **long-term agreements** (PPPs) for biomass and biochar. • Accelerate **scaling and learning processes** to develop the pyrolysis technology to large-scale. • Start **development of energy products for high-value use** and prepare possible upgrading, methanation and future coordination with PtX.	• **Categorisation of research results** according to evidence, biomass, pyrolysis process and area of application to make insights more practicable. • Initiate **long-term field studies** and gain an overview of the long-term environmental and agronomic impacts of use on agricultural land. • Develop **practical knowledge** for optimal use of biochar and exchange experience. • Extend **competence development,** training activities and learning tools for the people who are to develop, operate and administrate/supervise etc. biochar processes.
Specific recommendations	• **Equate pyrolysis plants with biogas plants** in the Planning Act to support possible location close to residual biomass. • Support quicker **environmental classification** of pyrolysis plants and thus the process for environmental assessments with outset in standard examples. • Adjust **phosphorus caps** with regard to biochar-release over time. • Work to get carbon storage with biochar **in other sectors**, for example the construction sector, recognised in national emission inventories (via the IPCC). • Develop **standard processes** for municipal assessments and section 19 permits, until central regulation is in place. • Establish a "**compliance assessment body**" to approve biochar with CE labelling as a fertilizer product.	• Develop **field management methods** for biochar (agriculture and materials suppliers). • Develop **combination of biochar and other fertilizer products** to achieve the best effects.	• Investigate the impact of biochar on **nitrogen leaching** from soil to the aquatic environment. • Examine the **interplay** between biochar, soil type, and the effect of different types of living organisms in the soil under Danish conditions.

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Annex A. Danish biochar production

A.1. Overview of pyrolysis plants in Denmark

There are currently around 12 pyrolysis plants (or equivalent) in Denmark that are either established or under construction, and that can produce biochar. This gives an expected total production capacity of just under 50 MW. Once the plants have been fully installed, it has been estimated that they will have capacity to produce biochar corresponding to net carbon storage of slightly more than 45,000 tonnes CO_2e. The information is based on data from producers and the sources mentioned. Note that the capacity of test and demonstration plants is not necessarily being fully exploited, just as not all research-based and test and demonstration plants have been included on the list.

Biomass	Location/ producer	MW	Biochar (tonne per year)	CO_2 storage in biochar (tonne per year)	Description	Sources
Straw	Brædstrup (SkyClean)	0,2	145	280	Fully automatic 200 KW pyrolysis test-facility. Can process 500 tonnes of agricultural waste and produce biochar with a carbon reduction of about 600 tonnes annually.	Stiesdal SkyClean Pressemeddelelse-Stiesdal-indvi-er-nyt-SkyClean-anlaeg-18.08.21.pdf
Straw (and manure)	Skive (SkyClean)	2	1.400	3.000	2 MW pyrolysis demonstration facility (May 2022) supported by the Energy Technology Development and Demonstration Programme.	Stiesdal SkyClean Laboratoriet for fremtidens grønne løsninger | Green Power Denmark
Chicken manure and straw	Horsens (Springkilde Bio/Frichs Pyrolysis)	3	900	3.000	Flash-pyrolysis (rapid heating to 800 degrees) with primary focus on extracting gas, but also biochar. Expected capacity of 15 tonnes of biomass every 24 hrs. The project also comprises a biochar spreader. Expected to start operation in mid-2024.	Frichs Pyrolysis Stiesdal, Dall Energy og Frichs Pyrolysis får knap 200 millioner klimakroner til udvikling (energy-supply.dk)
Manure and degassed residual fibers from biogas plants	Vrå (SkyClean)	20	14.000	26.000	Planned production equipment for pyrolysis of 20 MW in early 2024 that can process 40,000 tonnes biogas fibres annually and produce 14,000 tonnes biochar. Production can support an annual carbon reduction of min. 40,000 tonnes CO_2e in both storage and avoided emissions. Innovation project as part of Energy Cluster Denmark and with support from the Pyrolysis Pool to learn more about scaling, among other things.	Stiesdal SkyClean Stiesdal-pressemeddelelse-om-tildeling-af-midler-fra-Pyrolysepuljen-28.06.22.pdf
Sewage sludge	Fårevejle (AquaGreen)	0,7	400	500	Odsherred Forsyning has established a dehydration and pyrolysis plant with a capacity of 3,850 tonnes sewage sludge a year (850 tonnes dry matter), resulting in approximately 400 tonnes biochar with carbon storage capacity of 490 tonnes and with the CO_2e emissions reduced by 2,400 tonnes per year. Pyrolysis at approx. 650 degrees Celsius.	AquaGreen https://e-magasin.stf.dk/shared/spread/spildevand-2022-10-21-p60-61/jlfdaIGB

Sewage sludge	Søndersø (AquaClean og VandCenter-Syd)	0,7	400	500	Remediation and production installation (October 2021) with a capacity of 4,300 tonnes of biomass per year (slightly more than the total amount of bio-fertiliser from the north Funen installation).	AquaGreen Pyroplyse forvandler slam til bæredygtig gødning | Slam bliver til bæredygtig gødning – når vi snart sætter strøm til et nyt anlæg på Søndersø renseanlæg. Projektlederne Per og Niels præsenterer det... | By VandCenter Syd | Facebook
Sewage sludge (Microwave-assisted pyrolysis, MAP)	Skive (Organic Fuel Technology)	2	1.200	1.500	Demonstration facility which, using a patented microwave technology, processes 10,000 tonnes of sewage sludge per year/400 kg of dry matter from sewage sludge per hour. The products are bio-oil and biochar. The plant is under construction at GreenLab Skive with expected commissioning Q3-Q4 2025.	Organic Fuel Technology https://www.organicfueltechnology.com/oft-construct-plant-at-greenlab/ https://www.greenlab.dk/knowledge/new-partner-to-produce-green-fuel-in-greenlab-with-new-technology/
Sewage sludge	Harboøre Forgasseren	0,1	1	1	Heating plant in Harboøre which has been in production for several years. The plant is owned by B &W Vølund.	Harboøre Varmeværk A.m.b.A. (harvarme.dk) Trætjære og gas holder Harboøre varm - Skovdyrkerne
Sewage sludge	Lemvig (Lemvig Vand og AquaGreen)	0,7	400	500	The installation is under production and will be built by AquaGreen at Harboøre Renseanlæg at the start of 2024.	AquaGreen AquaGreen-anlæg i Lemvig - Nyheder - Automatik & Proces - Dit tekniske fagblad inden for automation og procesteknik
Sewage sludge	Tårnby (Tårnby Forsyning og AquaGreen)	1,4	800	1.000	The first sod turned in October 2023. Expected to be ready for use from 2025 (source). The plant will be the first HECLA 1,500 in Denmark and the fourth steam-drying and pyrolysis plant from AquaGreen in Denmark.	AquaGreen Pyrolyseanlæg (taarnby.dk)
Residual fibers from biogas plant	Vrejlev (Vrejlev Biogas/ Frichs Pyrolysis)	6	2.400	6.000	Pyrolysis plant integrated at Vrejlev Biogas ApS with expected start of operation from Q2 2024 and daily production of eight tonnes biochar based on 30 tonnes of dried manure fibres. Supported by funding from the Green Development and Demonstration Programme (GUDP) of DKK 14.5 mill. for construction. The project includes optimisation of residence time in the biogas reactor before being extracted for pyrolysis treatment.	Frichs Pyrolysis Hjorring - Etablering af pyrolyseanlæg på Vrejlev Bioenergi - Hjørring Kommune (niras.dk)
Various biomass residues	Esbjerg (DIN Forsyning, Dall Energy)	12	8.000	4.000	Large-scale pyrolysis plant. The plant will have a capacity of up to 65,000 tonnes of sludge and agricultural residues per year. The plant is expected to be finished in 2026 with a total climate impact of 16,500 tonnes CO2e including storage, displacement and avoided emissions. Has received funding from the Pyrolysis Pool of DKK 51.4 mill. The company also produces other biomass plants for district heating with specially patented gasification technology, but without biochar production.	Dall Energy New technology to benefit the climate and the environment: Dall Energy takes the lead with delivery of new, innovative pyrolysis plant (danskerhverv.dk) https://dallenergy.com/en_gb/biomass-projects/

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Annex B. Assumptions behind business cases

B.1. Overview of market assumptions - Assumptions used across the analyses

Parameter	Assumption	Source	Comments
Electricity prices	• Electricity prices dependent on consumption patterns	• The Danish Energy Agency Climate Status and –outlook 2022	• 2 pct. inflation – real 2021
Heating-prices	• 375 DKK/MWh	• Estimate based on inputs from i.a. Stiesdal	• The price of heating exports will vary from project to project • The same price is also assumed for process heat in case 4
Bio-oil prices	• 600 DKK/MWh	• Based on dialogue with potential consumers on take-up of a minimum of 600 DKK/MWh	• Based on expected bio-crude oil prices (incl. Expected price-changes cf. the Danish Energy Agency for traditional crude-oil)
Biochar sales price	• 0 DKK / tonne • [1.000 DKK / tonne as an alternative]	• Estimate based on inputs from i.e. AquaGreen	• It is primarily assumed that the biochar is not sold as a product but rather that the carbon sequestration is sold through climate credits.
Straw input-price	• 550 DKK / tonne	• The Danish Energy Agency Climate Status and –outlook 2022	• The market development might over time cause increasing prices on straw due to the demand and competitive characteristics
Sewage sludge - ”gate fee”	• 350 DKK / tonne • The business case requires a slightly higher price	• The Danish Environmental Protection Agency	• Currently, waste water plants offer payments to farmers who receive their sewage sludge and disperse it on their fields. The willingness to pay could increase, if the pyrolysis process can remove PFAS from the sludge with certainty.
Digestate input-prices	• 0 DKK / tonne	• Estimate based on inputs from i.a. Stiesdal	• The feed-stock is assumed to be cost-neutral due to co-location with biogas-facilities and no other economic value of the digestate
Inflation	• 2 pct.	• The National Bank	• Based on estimate for long-term growth rate of the economy
Tax rate	• 20 pct.	• The Danish Tax Agency	
Biochar distribution costs	• 50 DKK/tonne biochar	• Estimate based on inputs from i.a. Stiesdal	• Transportation costs from the production plant to the field and handling with respect to field application
Certification costs	• 160 DKK/tonne biochar	• Estimate based on inputs from i.a. Stiesdal	• Costs for certification of the biochar contents and placement in terms of meeting standard requirements
Biochar storage	• 22 DKK/tonne biochar	• Estimate based on inputs from i.a. Stiesdal	

B.2. Stiesdal SkyClean Introduction

Technology

- Stiesdal has developed a pyrolysis technology called SkyClean, with which they intend to convert agricultural waste into biochar and pyrolysis gas.
- The first commercial 20 MW plant is being built in Vrå, Denmark.

Technology

- The biochar produced by pyrolysis of the biomass binds a quantity of carbon, thereby preventing this carbon from being released into the atmosphere as CO_2. As the fuel is considered carbon-neutral, a SkyClean plant is considered as having negative carbon emissions.
- The pyrolysis gas can be used for many purposes e.g. as a heat source for drying or further processing to bio-oil or biogas

Production

- A 20 MW SkyClean plant can annually produce[1)]
- - Approx. 14 kt biochar, corresponding to about 26 kt CO_2e (100 years' capacity)
- - Approx. 68 GWh pyrolysis gas
- - Approx. 40 kt CO_2e total climate impact

Feedstock

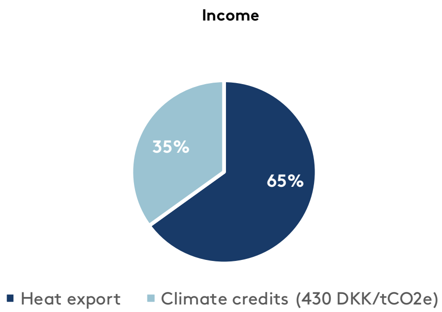
- The SkyClean technology can use a number of different fuels, including biogas digestate, agricultural waste and wood waste.

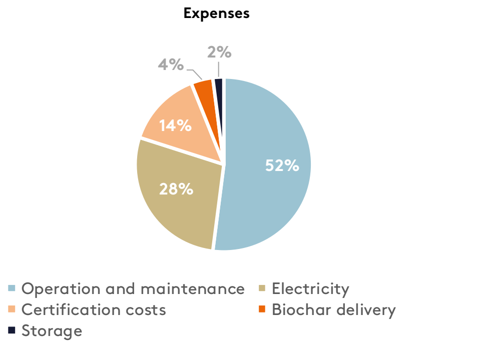
Economic benefits

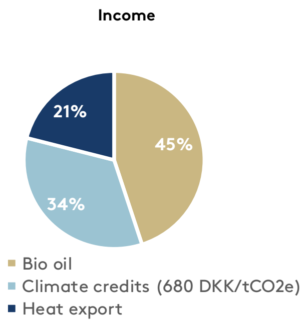
- As a SkyClean plant is considered to have negative carbon emissions, the amount of carbon stored in the biochar can be sold as climate credits on a voluntary climate credit market[2)]
- Stiesdal processes the pyrolysis gas so that can be used to produce various fuel products, e.g. bio-oil, biofuels for transport and SAF.
- The surplus heat produced in the process can be sold to nearby industry or the district heating grid.

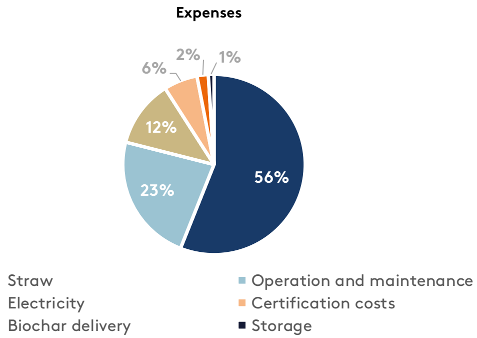
Kilde: Stiesdal.com

Business case: Residual fibres from biogas (Digestate)









1) The production data depends on the fuel used 2) Carbon stored in biochar can be sold on the voluntary CO_2 credit market.

B.3. AquaGreen HECLA Setores Introduction

Technology

- AquaGreen has developed a pyrolysis technology called HECLA Setores, which they have specialised to convert sewage sludge into pyrolysis gas for own consumption and biochar.
- Their first commercial installation is a HECLA Setores 1000 (around 0.7 MW) which is in operation in Fårevejle.

Technology

- The biochar produced by pyrolysis binds a quantity of carbon, thereby preventing this carbon from being released into the atmosphere as CO_2. As the fuel is considered carbon-neutral, a HECLA Sectores plant will have negative carbon emissions.
- The pyrolysis gas is used as a heat source for internal drying of the wastewater fuel.

Production

- A 2.6 MWth HECLA Setores plant can produce annually approx.[1)]
- - 1,764 tonnes biochar, corresponding to 2,375 tonnes CO_2e
- - 8,800 MWh heat

Fuels

- The HECLA Setores technology can be used various different types of sludge, and it has been certified that it can remove the PFAS content in sewage sludge.

Economic benefits

- As a HECLA Setores plant is considered to have negative carbon emissions, the amount of carbon stored in the biochar can be sold as climate credits on a voluntary climate credit market[2)]
- At present, there is a tipping-fee for sewage sludge, which means that wastewater treatment plants pay companies to take their sewage sludge. There is a large premium for sludge containing PFAS.
- The surplus heat produced in the process can be sold to nearby industry or the district heating grid.

1) The production data depends on the fuel used 2) Carbon stored in biochar can be sold on the voluntary CO_2 credit market.

Business case: Sewage sludge